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TECHNOLOGY SHOWCASE

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This book is dedicated to
COL Robert N. Leavitt, USMC
CDR Leonard King, USN (Ret)
and
CAPT Charles Rizzo, USAFR
who took the risks needed to improve the quality of the
JOAP.

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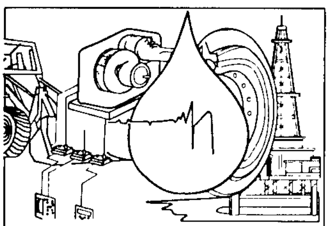
PREFACE

The 1998 Technology Showcase Joint Oil Analysis Program International Condition Monitoring Conference is designed to provide a medium for comprehensive technical information interchange which can be scaled to both government and commercial enterprises. The goal of the conference is to present an integrated picture of condition monitoring as a vital maintenance function for both technical and management personnel. The world is getting smaller and competition for assets is becoming greater day by day. Hence, we must continually search for new technologies to improve quality, productivity, efficiency and reduce costs. One must remember that on-going systems improvement is a necessity to keep customers satisfied. Happy customers are the key to success. As we enter the new millenium, we cannot forever rest on past laurels and the fruits thereof.

Randy Holland
Technical Director
JOAP-TSC

Sponsor:

The Joint Oil Analysis Program - Technical Support Center (JOAP-TSC) serves as the cognizant engineering authority for used-oil analysis methods, tribology methods and test instruments for the US Department of Defense. The JOAP-TSC monitors data measurement quality and reliability for over 360 laboratories worldwide. The center coordinates management and technical support to the United States Armed Forces, US Government agencies, DoD contractors and Allied Nations. JOAP members strive to protect personnel and extend the life and reliability of valuable aeronautical, ground and marine assets.



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Co-Sponsor:

The University of Wales, Swansea, Mechanical Engineering Department in conjunction with the Swansea Tribology Center is actively involved in research and development of equipment and fluid monitoring technologies. Since 1984, the University of Wales has sponsored several international conferences on machinery condition monitoring around the world. The Swansea Tribology Center provides a focal point for those involved in tribology and equipment condition monitoring and supports commercial and military equipment monitoring programs in the United Kingdom and other countries.

THE FUTURE DIRECTION AND DEVELOPMENT OF ENGINE HEALTH MONITORING (EHM) WITHIN THE UNITED STATES AIRFORCE

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ABSTRACT

1. The ability to trend an engine's health & performance has been possible ever since Hero of Alexandria fired-up his steam driven Aerolipile in around 100BC. However, the development of any engine health monitoring (EHM) system has historically been driven by a need to resolve an operational dilemma. Unfortunately the goal of EHM technologies has sometimes never been clear or achievable because the described problem and need have not been fully understood; so the realization of the ability to monitor and predict an engine's life, health and performance has never kept abreast with the technology it is trying to support.

2. The DOD's is developing engines towards increased power to weight goals with a need to show reduced life cycle costs and improved reliability; obligating major advances in control, diagnostic and prognostic technologies. The acquisition of real-time engine data is already achievable, however the interpretation and utilization of such data is still difficult, even after 2000 years. Current activities that are being investigated for the development of EHM technologies will demonstrate a cognitive (acquire knowledge) ontogenetic (learning) monitoring ability that can accurately predict a gas turbine engine's health (the overall soundness) performance variation (degradation), component life (e.g. LCF, HCF and Creep) consumption based on real or virtually sensed engine data. Therefore the development of an aware, learning and reasoning EHM system is the missing link between our current diagnostic confused situation, and a status of having a true diagnostic with prognostic (knowledge with wisdom) capability.

3. The USAF's research & development activities are firmly assisting in the evolutionary work that is required to provide a future EHM system that is artificial intelligence (AI) based. This paper will detail the EHM activities that are currently being investigated to achieve the process of turning data into information into knowledge and finally into wisdom. Moreover it will focus on describing the approach and bias that must be taken on the development of a gas turbine EHM system for health and life management. It will define how data integrity, compression and fusion will feature as the first link towards achieving a truly cognitive ontogenetic (CO) (aware and learning) EHM system. Additionally by developing and applying reasoning science, like that provided by a probabilistic diagnostic and prognostic system (ProDaPs), we can then achieve an assemblage that could be described as truly artificially intelligent; namely in structure, judicious reasoning and execution. These activities will bring about philosophies, methodologies and technologies to make accurate predictions and provide technical solutions to reduce an engine's life cycle cost, enhance flight safety and strengthen operational capability.

THE ENGINE MONITORING (EM) GOALS

4. The increasing emphasis on improved affordability, availability and safety prompted has prompted an investment in improved embedded engine diagnostic technologies; this approach has been called 'Autonomics'. The focus of this investment was to select the "low hanging fruit," i.e. the relatively high value low risk problems. Although extensive improvements in diagnostic capability for controls, accessories and lubrication system components have been incorporated in the latest generation engines, the diagnostic coverage for gas path does requires further development. Problems with gas path structures relate to approximately 30% of current fighter engine in-flight shutdowns.

5. The DOD's/USAF's Integrated High Performance Turbine Engine Technology (IHPTET) goals for performance, weight reduction, reliability and life cycle costs will need accurate and timely data. These objectives will only be achieved through an EM system that provides real time monitoring and health information. Therefore IHPTET needs a COEHM system that will monitor, trend, diagnose, predict and inform. This paper addresses some of the research and development programs and the required methodologies that will help achieve real time AI EM. The goal is to have the right action at the right time for the right reason, i.e. the 3 Rs of EHM.

EM DEVELOPMENT

6. The development of an AI EM system will need to use tools such as data filters, polynomials, fuzzy logic, expert systems, probabilistics and neural networks. This list is not exhaustive and will require the application of novel approaches to give the system the ability to make accurate prediction before the event it is monitoring happens. A COEHM system will provide fast and accurate diagnostic and prognostic information to reduce maintenance times, no fault founds and turn round times. The improved critical life management aspect will reduce engine life cycle costs. Therefore the development of a COEHM system will considerably reduce engine cost of ownership, enhance operational capabilities and overcome loss of technical experience due to personnel downsizing.

COEHM METHODOLOGY

7. The COEHM Methodology approach (pictorially shown at fig 1) requires an integrity

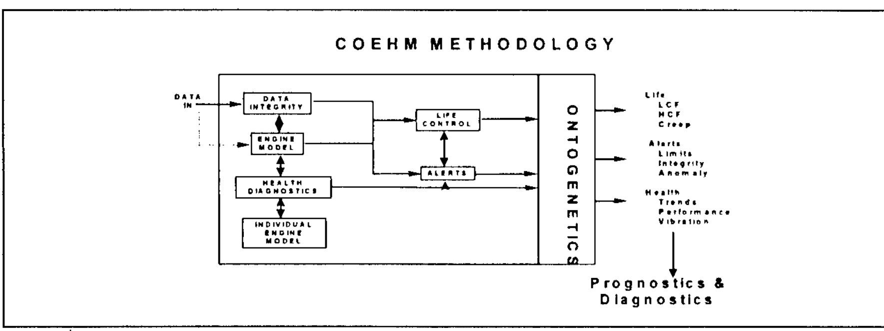

Fig 1

check through a Data Integrity Module for all data inputted and will compare this to empirical data as well as real time model data from the Engine Model Module. The Engine Model Module feeds accurate data for real and derived parameters into the Life Control, Alerts and Diagnostic Modules. The Health Module will be able to make comparisons between the data coming from the engine, those derived from the model and those

performance curves that were obtained during engine pass off and are now contained within the Individual Engine Model Module. The system feeds life, alerts and health data directly to maintenance staff or can be feed through an Ontogenetic Prognostic (i.e. true AI) Module that will improve the probability of identifying the outcome of current or future events; this final module will give the maintainer a true diagnostic and prognostic capability that is accurate and fast. As a modular approach the system concept can be modified to meet the needs of the user and as such can be applied to aging aircraft as well as those currently in service and planned for the third millennium.

8. **COEHM Model Based Diagnostic & Performance Algorithms**. The Engine Model Module is a model based diagnostics system, which can be used to improve performance, increase reliability and sortie generation rate, and so reduce maintenance costs. This system features a real-time, nonlinear, physics based, dynamic model of the engine embedded in the engine controller (FADEC) or as part of the EM system. This model is updated in real-time using a tracking filter to match actual engine characteristics. Model computed values can then be passed to the Health & Diagnostic Module. Some gas path structural failures occur with significant precursors identifiable in performance parameters. To date normalizing performance parameters sufficiently to detect and isolate these precursors has been difficult. The advent of adaptive on-board performance simulations has provided normalized gas path performance parameters that are proportional to changes in engine module performance. This methodology utilizes these parameters and a neural network to improve detection accuracy.

9. **COEHM Health & Diagnostics Approach**. Advancing the USAF's capabilities in engine life measurement, diagnostic and prognostics capability of critical engine components is necessary to improve engine availability, minimize performance degradation, and reduce life cycle costs. Engine data currently sensed and recorded for post flight processing can be analyzed in a continuous real-time mode within the Health & Diagnostic Module. Proven AI technologies such as neural networks, fuzzy logic and expert systems present an opportunity to significantly enhance current trending and diagnostic capabilities in a real-time monitoring environment. For fault detection and accommodation, extensive knowledge of how a healthy engine operates under given conditions will be analyzed, and any deviation from this 'normal' pattern of expected parameters will be detected and further analyzed. The same sensed data will be used as inputs to life usage algorithms in the Life Control Module and will determine critical component remaining life based on actual experienced severity.

10. **Probabilistic Method (PM) for Life Management and Diagnostics**. The use of PM for the development of improved design and life sensitivities has been achievable for some years, and we can now more accurately design and life a component. The growth in computing power has freed this statistical tool and allows the application of resolving tools such as Monte Carlo, Second Order, Taylor Expansion, Orthogonal Array etc. The extension of PM for the production of generic High Cycle Fatigue (HCF) codes will require validation and verification (V&V) of the sensitivities that were applied. The function of a PM V&V tool would be ideally suited to run concurrent with the component, so as to assure that the real time experience reflects the one assumed at the design stage.

11. The ability of a PM code to apply sensitivity to data will further increase the chances of identifying the cause of an engine's fault (diagnostics) or deducing the most likely health or performance outcome (prognostics). Probabilistic as a real-time diagnostic, prognostics and life management tool will be an important contributor to producing a COEHM as well as to help meet the IHPTET goal of reducing maintenance costs. The application of a global genetic 'optimization' probabilistic tool will improve the sensitivity for diagnostic and prognostic speed and accuracy. The use of P M for V&V, fault isolation, identification and prediction still needs further development.

12. **Probabilistic Diagnostic and Prognostic System (ProDaPS)**. The development of a probabilistic diagnostic and prognostic system (ProDaPS) capability for turbine engine health is achievable. It will assist in the development required to provide a future predictive methodology that is able to deduce accurately the outcome of an event, so as to reduce engine life cycle costs and enhance operational capabilities. ProDaPS will provide real-time diagnostic and prognostic assessment of creep and fatigue life, component condition

and life consumption, engine performance and engine health. The system will also integrate performance and historical information to produce its own COEHM capability. The system will ultimately have the ability to V&V probabilistic design and life codes and thus confirm that the assumed PM sensitivities are accurate.

DATA NEEDS FOR A COEHM SYSTEM

13. **'Total System' Sensing**. The need for data integrity is a corner stone of an effective COEHM approach, and the ability to model real time data or virtual data l are major steps towards a true understanding of the engine's health. However there is a need for a more 'total system' approach to sensing data and this is pictorially shown at fig 2. A 'total system' approach to data sensing will require the application of new advances in sensing technology. The concerns about any sensing expansion is weight and reliability and so the approach must be towards

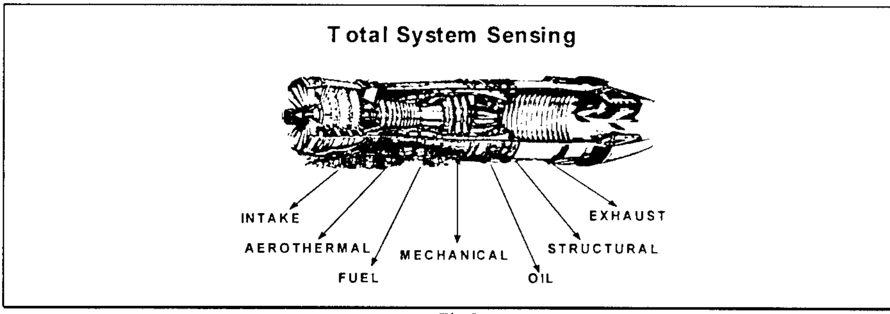

Fig 2

function amalgamation and simplification, e.g. we will develop sensors and methodologies that will perform both vibration and speed or temperature and speed monitoring. The development of more passive sensors will improve reliability in that they only need to detect changes in amplitude or frequency.

14. **FOD Detection & Exhaust Emissions Analysis** . The increasing complexity of modern aircraft inlet structures will increase the maintenance burden for routine inspections for Foreign Object Damage (FOD). FOD detection technology (acoustic, radar or electrostatic) will reduce the maintenance burden by providing an automatic FOD detection capability; it does require detailed signature profiles of events to be effective. The systems are:

a. **Acoustic.** The acoustic approach utilizes close coupled high response pressure transducers and advanced signal processing to detect the acoustic energy emitted when a engine fan blade is impacted by a damaging foreign object. This concept focuses on the characterization of the acoustic signal generated by impact and the detectability of that characteristic within the normal engine background noise environment. Laboratory and engine testing demonstrated that this detection technology is practical with high accuracy for cases of blendable FOD.

b. **Radar**. The radar approach was initially designed to detect blade damage. The system uses a low power radar emission and detection system within the inlet; this approach has already been able to detect 1mm defects in blades as far back as the compressor's third stage. The system goal is to determine the type and characteristics of all possible FOD ingested by an engine. The technology can already derive velocity and relative mass and can determine the difference between a split pin and other metallic objects.

c. **Electostatic**. The electrostatic approach monitors both the inlet and outlet gas path. It employs an electro-magnetic detector in the inlet as well as one in the outlet. The system monitors the change in ionization of the gas path and is more complex than the approaches detailed above and as such requires a

high rate of data acquisition and considerable computer power to perform diagnostic and prognostic evaluations. Electrostatic Engine Monitoring (EEM) has been a technology that has shown promise since the early 1970s. Many evaluations from laboratory, to engine and flight testing have shown that material within the engine gas path is detectable as charge particles either entering or exiting the engine gas stream. The early attempts to employ this technology were troubled by false indications and problems in setting thresholds for normal versus abnormal signatures. New sensing electronics and signal processing software promise to overcome these problems.

15. **Non Synchronous Vibration - HCF**. The failure of an aircraft's gas turbine engine can be catastrophic. Similarly, millions of aviation industry maintenance man-hours are spent each year inspecting for the precursors to HCF damage. HCF is caused by resonance, and whilst its effects in a gas turbine can be reduced by avoiding/eliminating resonance at the design stage, changes in usage or configuration can unknowingly introduce HCF. HCF differs from Low Cycle Fatigue (LCF) in that the fatigue mechanism from varying loads of smaller amplitude but much higher frequency. This will cause rapid propagation of a crack and lead to failure in a short time. The combinations of parameters which generate HCF are much more difficult to define and predict, than the well characterized conditions which are associated with LCF. An accurate and effective means of monitoring HCF damage and diagnosing it would be essential for COEHM system.

16. **Real-Time Vibration Monitoring & Improved Vibration Analysis**. The need to measure true individual blade vibration is essential to any active vibration control system or to accurately deduce where a component is on its life to failure curve. The current technology of using accelerometers is adequate for determining out of balances or identifying a pump malfunction, but they have application and environmental limitations. Therefore new approaches are required to the measurement, in real time, of vibrational forces being experienced inside an engine. The technologies that could be used are almost limitless, but some of the current thinking is towards:

a. **Acoustic**. Required only to pick up the acoustic changes in a passing blade, but does require an expert interpretation of the resolved frequencies. The sensor is passive in that it only receives and has no emit requirement. The rotational speed as well as pressure can also be easily monitored.

b. **Blade Tip Deflection Sensors**. This system uses time measurement to determine the dynamic tip deflection. The optical probes are located over the blades being monitored and laser light is used to detect changes in the position of a blade, and as such can be directly related to vibration2. The reflected light process is more complex than an acoustic sensor but can provide rotational speed as well as thermal data when used in conjunction with thermographic phosphors.

c. **Eddy Current**. With a eddy current probe mounted on the shaft then any changes in an electro-field can be resolved directly into a vibration. The system can also deduce rotational speed and torque. The inherent property of a rotating mass is that it vibrational signature changes dramatically if it has a defect, and as such this approach could also detect blade or disc cracks.

d. **Oil Monitoring**. The use of in line real time oil monitoring3 will identify the mass and density of any bearing material in the oil system. As bearing break-ups follow a characteristic burn out curve the comparison of vibrational data and bearing debris data will help identify more accurately incipient bearing failures.

17. **Real-Time Crack Detection**. The ability to accurately design and so predict a defect free component is driven by the need to control life cycle costs within technology constraints. The greater the need to produce a defect free component then the greater are the potentials to gain additional cost or performance benefits (design and manufacturing cost reductions, weight reductions, life extension and improved damage tolerence). However there will never be a point of zero failure and so we must consider the need for a real-time crack detection system. The current technologies would lend to the development of a system to detect cracks using eddy currents or X-Ray Tomography4.

IMPROVED LIFE ALGORITMS

18. The effectiveness of monitored data depends on how it is interpreted The used of life algorithms are well understood to equate a total life as well as deduce a life used. To date the accuracy of these algorithms have been adequate, but a more precise approach is now required. The tracking of engine usage has progressed from manually recorded engine operating time to today's standard of total accumulated cycles based on monitoring of speed gates. Even today's approach, however, is a rough approximation of actual life consumption during normal engine operation. These rough approximations result in considerable uncertainty in setting inspection intervals, and can result in inspections occurring too late, impacting safety or too early, impacting availability. The development of advance life algorithms rely on design structural analysis equations and on-board measurements to improve accuracy. The use of Probabilistic as a design and life tool was defined at para 10 and reflects the current thinking on more accurate life predictions.

CONCLUSION

18. The USAF has set itself goals for capability, performance and reliability standards that it must achieve if it is to maintain air superiority. The advent of novel design methodologies and materials has put the spot light on engine diagnostics and prognostics as an essential element to achieve those goals. The development and implementation of the COEHM Methodology will help meet the set Autonomics goals and the needs of the third millennium. The development of a totally sensed engine (real or virtual) that provides exact and accurate data will help a COEHM system perform the AI function that is required to derive fast and accurate answers; this will enable the maintainers to quickly regenerate an aircraft for it next mission. The COEHM is more than just an approach but an asserted effort to produce a range of compatible EM systems for 2001 and beyond.

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The Development of Technological Support for RAF Early Failure Detection Centres

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Abstract: Because of staffing policy within the Royal Air Force, personnel are rotated on a regular basis. This can often result in an experienced member of a team being replaced by someone with minimal knowledge of the job. This is true of Early Failure Detection Centres (EFDCs) which perform first line Equipment Health Monitoring (EHM) at RAF air-bases. Experience is probably one of the most powerful tools in EHM and, in particular, debris monitoring; therefore, there is an ongoing need for the development of condition monitoring systems and techniques that will assist RAF EFDC staff new to the post. The RAF use a number of modern analytical techniques in their EFDCs, including optical microscopy, image analysis, Scanning Electron Microscopy with Energy Dispersive X-Ray (SEM/EDX) micro analysis packages and Energy Dispersive X-Ray Fluorescence (EDXRF) analytical equipment. Therefore, the need exists for equally sophisticated, but user-friendly tools that will aid the EFDC operative in the everyday job of EHM. For a number of years the Mechanical Engineering Department, University of Wales Swansea and the Defence Evaluation and Research Agency (DERA) Fuels and Lubricants Centre, Pyestock have been collaborating on such projects, funded by the Ministry of Defence. The aim of this paper is to give a summary of the work so far and to outline intended future programmes.

Key Words: Computer aided ; CASPA; CAVE; debris analysis; Early Failure Detection Centres; equipment health monitoring; Royal Air Force; Wear Particle Atlas.

Introduction: Wear particle analysis is a powerful technique for non-destructive examination of oil-wetted parts of an engine. The particles contained in the lubricating oil carry detailed and important information about the condition of the machine. This information may be deduced from particle shape, composition, size distribution and concentration. The particle characteristics are sufficiently specific so that the operating wear modes within equipment may be determined, allowing prediction of the imminent behaviour

of the machine. Often, action may be taken to correct the abnormal wear mode without overhaul, whilst a timely servicing can prevent costly secondary damage.
The Royal Air Force operate a number of aircraft types that are not amenable to spectrometric oil analysis. Therefore, the routine analysis of wear debris collected on magnetic drain plugs situated within the aircraft's lubrication system is the primary condition monitoring technique. Interpretation of the morphological characteristics of debris is vital in Equipment Health Monitoring and requires a combination of analytical, metallurgical and engineering expertise, relying heavily on the experience of the operator. The regular turnover of personnel in RAF EFDCs means that there is insufficient time for an individual to develop the necessary skills required to carry out this type of specialised analysis. This has led to the need to introduce procedures which assist in formalising the decision-making process in order to provide systematic and objective methods of analysis. This is an area that computer-based systems are ideally suited and has provided the basis of the development work at Swansea. While some of the techniques described in this paper have been reported previously, it is worthwhile recapping on this past work and giving a brief resume of recent progress [1].

Computer-Aided Morphological Analysis: The purpose of utilising computer-aided systems for analysing particle morphology is to establish the reliable identification of a specific wear particle, linked with a capability to document the information and prepare a report defining the results of the overall analysis of the sample. Coupled with other information about the sample, it should also be possible to formulate an accurate diagnosis of the wear condition and identify the associated fault in the system.
Morphological analysis requires that debris is examined using an optical microscope, enabling the analyst to determine the pertinent attributes of the sample. The particular features of interest are particle size (plain dimension and thickness), outline shape and edge detail, surface features and colour [2]. This type of examination is time-consuming, tedious and invariably subjective, but essential if the type, cause and severity of wear is to be determined. With these points in mind, a number of methods have been developed exploiting modern computerised procedures, incorporating the use of neural networks and image analysis techniques.

CASPA: The Computer Aided Systematic Particle Analysis (CASPA) system has been developed as a Windows-based software package that trends and classifies wear debris [3]. This is achieved by means of a number of dialogue boxes that questions the operator, leading to the diagnosis of the debris type-Figure 1. The first box, *Module Record* contains a chronological list of the debris samples collected from one source i.e. sample point or engine. The *Sample Record* stores the engine operating hours, the debris concentration (as measured e.g., by the Wear Debris Tester, or the Particle Quantifier [4], and any comments relevant to the interpretation of the sample.
The *Particle Dialogue Box* prompts the operator to describe the particle under observation by means of a number of descriptors, these include particle shape, edge detail, surface texture and colour. From these features the system is able to identify the particle type and give the result to the operator in the *Diagnosis Box*.
There are a number of benefits to a diagnostic tool of this nature. Namely, it establishes a systematic and objective procedure to arrive at a reliable identification of a specific particle type, whilst linked to a capability to prepare a report defining the results of the overall analysis of a sample. Major advantages of CASPA is that, as an expert system it may be

used by inexperienced personnel, while repeated use will train the operator in the recognition of specific wear types.

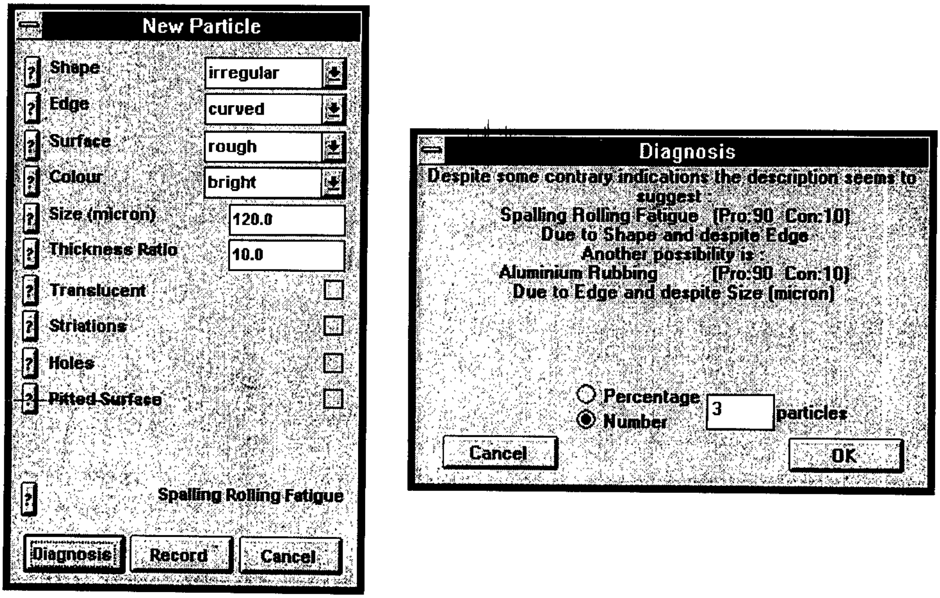

Figure 1 CASPA dialogue and diagnosis system

CAVE: The Computer-Aided Vision Engineering (CAVE) program has been developed as an automated particle recognition package to quantify analysis of a particles size and shape [5]. The system uses image analysis techniques to extract information about a particle from captured video images. The addition of neural network procedures has enabled the system to be trained to produce classification of particle shape, as well as recognising the surface features of a particle in relation to the associated wear mode.
CAVE can be utilised to calculate various features of a particles shape including size (area and maximum length), aspect ratio (proportion of length to width), roundness factor (perimeter^2/4π area), Fourier coefficients of outline and outline curvature. Outline curvature is a useful, size-independent and rotationally neutral description of the shape of a particle. The statistical moments of curvature give a measure of a shape's regularity and edge detail and the first eight harmonics of the Fourier transform of the outline curvature have proved a satisfactory input for the neural net classification of particle shape.
Despite being developed primarily for the analysis of MDP samples, some difficulties have been experienced with the application of CAVE due to the current procedures for sample preparation in RAF EFDCs. This issue is currently being addressed, as it also affects the efficiency of other analytical techniques recently introduced by the RAF.

Wear Particle Atlas: The purpose of developing a series of annotated images is two-fold, it provides a reference document for debris associated with specific engine types and can also be used for tutorial sessions during the training of inexperienced personnel. The process used in the development was Hyper Text Mark-up Language to generate hyper-linked text and images, comprising scaled images of debris, galleries of "thumbnail" images with explanations of components and other relevant information [6].
Two type-specific Wear Particle Atlases (WPA) have been produced; one for the Rolls Royce RB199 engine and the other for the Allison T56. Both are formatted in a similar manner and provide information for the identification of various wear particle types found in each engines lubrication system. Each atlas provides information for the identification of these particles and the wear modes that generate them.

Visual CASPA: Incorporated within the current WPAs is technique called Visual CASPA. Like the earlier version of CASPA, this will aid the inexperienced operator in the identification of a wear particle type. Visual CASPA uses a decision tree method to analyse particles and requires the operator to select certain options from a list of morphological attributes based upon the unknown particle. These attributes are presented to the user in the form of stylised images. Once a particle has been selected for analysis, various questions are asked by the program, which narrows the search down to a specific particle type. At each stage, Visual CASPA will announce the number of particles that conform to the answers given so far. For example, if the particles shape was chosen to be irregular and the edge was considered rough, eighteen particles within the WPA have both theses attributes. These can be displayed at this stage or, by answering more questions, further particles can be eliminated. Once the number of conforming particles is small enough, a gallery of thumb nail images is displayed. From this, a match can be made and a full size image will be shown with a brief description of the particle.

Current Developments: Effective health monitoring often depends on the subjective assessment of a debris sample, because the links between morphology of wear particles and the wear processes that lead to their production are not fully understood. Debris monitoring depends on a knowledge of the processes of wear and failure, and how these processes generate particles with specific size distributions, morphologies and surface textures. There are many conditions possible in lubricated components which give rise to wear mechanisms from mild wear to severe scuffing and a variety of characteristic debris types. These need to be characterised by a controlled study of the effect of load, speed, environment and the type of lubricant, the results being used to produce a 'wear atlas' or map of the wear mechanism types and characteristic debris generated. Work has begun on the development of a Generic WPA for use by EFDC staff. This will involve the characterisation of the morphology of wear debris particles produced under controlled conditions, or alternatively, are taken from known conditions that can be verified as having occurred. The relationship between wear mode and the characteristics of the debris generated will be examined, with particular emphasis placed on relating particle morphology to predicting equipment health. The final version of the Generic WPA will contain high quality optical and SEM images of debris, with associated descriptive text and a decision tree similar to Visual CASPA, using stylised images of generic debris types and classes. Once the Generic WPA has been completed, it is intended that modules are added, specific to individual aircraft/engine types, containing images of typical debris, compositional and component specific information..

Conclusion: In the development of the techniques described in this paper, a number of points have had to considered. Any procedure devised for use within the EFDC environment must be clearly defined, easy to follow and quickly executed. Thought must be given to the compatability with other facilities and procedures already in place, while at the same time being helpful and reliable in assisting EFDC staff make a fast and accurate diagnosis.

With constant cut-backs on Defence spending, cost of new equipment is a major issue. There is no point, therefore, in developing a piece of equipment, no matter what benefits it offers, if it is prohibitively expensive to produce. The advantage of the systems discussed in this paper is that only a standard personal computer and an optical microscope are required to use them. With careful thought on the implementation and further development of these systems, it is expected that the RAF will be provided with a very powerful EFD diagnostics tool.

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ENGINE CONDITION MONITORING SYSTEM FOR THE CANADIAN FORCES F404-GE-400 ENGINE

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Abstract: With the acquisition of the CF-18 fighter aircraft in 1982, the Canadian Forces have developed advanced engine condition monitoring techniques and software programs to aid in the life cycle management of the General Electric F404-GE-400 engine. The early programs that provided parts life and engine maintenance tracking have recently been replaced by PC-based, graphical user interface systems that not only provide configuration and usage management, but have diagnostic and prognostic capabilities as well. These developments have made the Engine Condition Monitoring System (ECMS) unique among F404 users and have conclusively demonstrated significant resource savings in terms of personnel and spares procurement in addition to increased effectiveness at all levels of maintenance. This paper describes the Engine Condition Monitoring System and the impact it has had on the CF-18/F404 engine maintenance program.

Introduction: The air element of the Canadian Forces operates 103 CF-18 fighter aircraft from main operating bases located in Cold Lake, Alberta and Bagotville, Quebec. Each CF-18 is powered by two General Electric F404-GE-400 engines, a twin-spool, afterburning turbofan with a maximum thrust rating of approximately 16,000 pounds.

The acquisition of the CF-18, by the Canadian Forces, has resulted in a new approach to fighter engine maintenance. In particular, an on-condition maintenance philosophy has been adopted whereby maintenance actions are dictated primarily by observations and/or measurements of actual engine condition rather than on a fixed frequency basis. This new approach is made possible by the design features of the engine (e.g. modular construction and borescope access) and by the aircraft's In-flight Engine Condition Monitoring System (IECMS).

In 1983, the Canadian Forces initiated the development of an Engine Condition Monitoring System (ECMS) to capture the IECMS data in a single integrated database which could be used for decision support at all levels of F404 engine maintenance. The early development of this system is described in References [1] and [2]. This paper describes the present system and the impact it has had on the effectiveness of F404 engine maintenance.

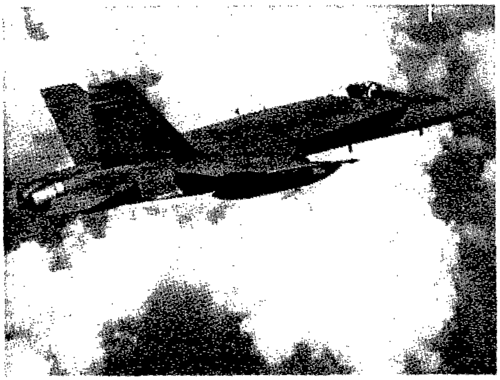

Figure 1 - CF-18 Aircraft (Canadian Forces Photo)

In-flight Engine Condition Monitoring System: Each CF-18 is equipped with a fully integrated In-flight Engine Condition Monitoring System [3]. The IECMS logic is implemented as software on the aircraft Mission Computer and includes the following major monitoring functions:

1. **Life Usage Evaluation** - Engine low cycle fatigue, thermal fatigue and creep damage are evaluated by eight Life Usage Indices (LUIs). Running sums of each LUI are stored in the Mission Computer memory and are recorded to tape twice per flight.

2. **Operating Limit Surveillance** - The IECMS continuously monitors the status of the engine fan speed, compressor speed, exhaust gas temperature, oil pressure and vibration signals with respect to predefined limits for safe operation. If an exceedance is detected a cockpit caution is activated, a three-digit maintenance code is set at the Maintenance Monitor Panel (MMP) located in the aircraft nose wheel-well, and approximately 40 seconds (5 seconds pre-event, 35 seconds post-event) of engine/aircraft performance data are recorded.

3. **Sensor Failure Detection** - The IECMS logic checks that the fan speed, compressor speed, compressor delivery pressure, exhaust gas pressure, engine inlet temperature and engine oil pressure signal levels are within normal operating ranges. If a sensor failure is detected, an MMP code is set and a 40 second data recording is taken as described above.

4. **Flameout Detection** - The IECMS logic also includes a flameout detection algorithm based on the behaviour of the compressor delivery pressure and rotor speed signals. If the IECMS criteria for flameout are satisfied, a cockpit caution is activated, an MMP code is set and a 40 second event recording is initiated.

5. **Take-off Thrust Evaluation** - The IECMS automatically records engine and aircraft performance data during the ground roll of each take-off for the purpose of engine performance evaluation. A computed thrust value based on measured exhaust gas pressure and nozzle position is provided for cockpit display and is included as one of the recorded parameters.

6. **Pilot Activated Recordings** - The IECMS logic enables the 40 second event recording feature of the system to be activated by the pilot using a switch located in the aircraft cockpit.

The IECMS data recordings are stored in the form of coded messages on a cartridge Tape Transport Magazine (TTM) that is removed for ground-based processing. Under normal aircraft operations, the TTM capacity is roughly 7 to 10 flights, after which the tape is downloaded, processed and its relevant contents stored in the ECMS database. If an in-flight engine event occurs (i.e. an MMP code is set) or a manual recording is initiated, the TTM is downloaded immediately for troubleshooting of the incident.

F404 Maintenance Concept: Maintenance policy for the F404 engine is based on a judicious balance of scheduled, corrective and conditional maintenance, supported by appropriate modification action. Accurately determining this balance is of paramount importance. Excess scheduled maintenance will lead to reduced aircraft availability and inefficient use of manpower and other resources. On the other hand, insufficient preventive maintenance will lead to an increased need for corrective maintenance, with the associated adverse effects on safety, aircraft serviceability, mission reliability and, possibly, life expectancy of the engine. The ECMS was designed to work within this framework to achieve an optimum balance between the five CF maintenance policy objectives which are to:

a. minimize faults that could produce situations hazardous to the engine, aircraft or personnel;
b. minimize faults that could cause an unacceptable loss of operational capability;
c. minimize the amount of technical manpower and other resources required for maintenance;
d. minimize faults that could result in lengthy downtime and/or expensive repairs; and
e. identify methods of improving reliability and/or maintainability.

Corrective Maintenance: Corrective maintenance comprises maintenance activities carried out on and off the engine after a fault has occurred, in order to restore the engine to a serviceable state. It includes work undertaken to confirm a fault, to diagnose its cause(s), and to complete the necessary repair, replacement and operational or functional

checks. An example of corrective maintenance is the replacement of a defective Line Replaceable Unit (LRU) on the engine (e.g. a Main Fuel Control)

Preventive Maintenance: Preventive maintenance is carried out to provide safe and trouble-free operation of the engine and its accessories. It consists of systematic and prescribed work undertaken to reduce the probability of failure, and to ensure that performance is not degraded by time or usage. The determination of preventive maintenance requirements is central to the maintenance plan, since it determines or influences the scope of almost all subsequent activities.

Within the CF, all preventive maintenance requirements are assigned to one of three primary maintenance processes:

a. On-Condition Maintenance (OCM). A primary maintenance process of repetitive inspections or tests to determine the condition and continued serviceability of systems, portions of structure, or items. Corrective maintenance is taken, when required, based on item condition.

b. Hard Time Maintenance (HTM). A primary maintenance process in which an item must be removed from service at or before a specified time or number of cycles, i.e., the item is lifed; and

c. Condition Monitored Maintenance (CMM). A primary maintenance process that is initiated as a result of knowledge of an item's condition gained from periodic or continuous monitoring. Where adequate and realistic condition monitoring techniques exist to detect incipient failure, Condition Monitored Maintenance is applied to the item in preference to OCM or HTM, respectively.

Maintenance Levels: Maintenance on the F404 spans three organizational levels. The first level is maintenance that is directly concerned with maintaining the engine in a serviceable condition. Here, first line technicians troubleshoot an engine unserviceability and replace LRU's to bring the engine/aircraft to a serviceable state. If the problem is beyond the ability of first line technicians, or a lifed item has time expired, then the engine is removed from the aircraft and sent to the next level of maintenance. Second level maintenance is accomplished at the base engine repair facility. At second level, the engine and its individual modules can be completely torn down, inspected and reassembled. Maintenance at this level is also supported by a fully computerized engine test facility where every engine that is inducted into second line will be tested before being declared "ready for installation" (RFI). The third level of maintenance support on the F404 conducted by commercial contractors who repair and replace components which have been deemed faulty and cannot be repaired by first or second line technicians.

F404 Maintenance and the ECMS: Figure 2 depicts the general flow of data and information in support of F404 maintenance and the role that the ECMS plays as a decision support tool. As previously noted, the CF-18 IECMS continuously and automatically monitors and records F404 **usage** (operating hours, mechanical and thermal

fatigue cycles and time at temperature counts), **health** (as determined by engine take-off performance characteristics) and operational **event** data which, in turn, are stored in the ECMS database. Two additional types of information are also input manually into the system database: **configuration** data defining the makeup of each engine in terms of its constituent components and **reliability** data which record specific engine problems, their symptoms and the maintenance activities required to rectify the problem. The ECMS holds the Maintenance Plan for the engine as defined by the preventive maintenance activities and their intervals, the usage limits for life-limited components, the limits specified for health indicating parameters, the fault library which relates health index patterns to specific engine problems and the troubleshooting logic used for fault isolation. In addition to providing day-to-day decision support for the preventive and corrective maintenance processes, the ECMS also provides a database which can be used to continuously refine and improve the engine maintenance plan and, hence, the effectiveness of F404 maintenance.

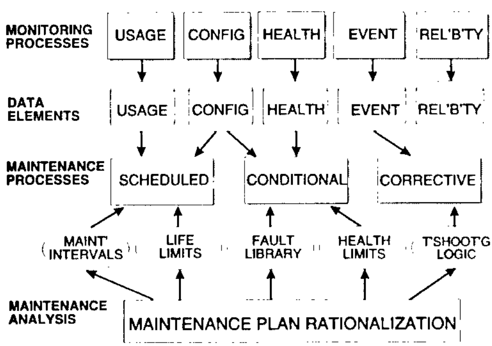

Figure 2 - ECMS Database

ECMS Description: The ECMS is a PC-based maintenance information management system which provides decision support to all levels of the F404 maintenance program. As illustrated in Figure 3, the system operates simultaneously over Local and Wide Area Networks which link together system elements located at each squadron, the two main CF-18 operating bases (CFB Cold Lake and BFC Bagotville), the 3rd line engine overhaul contractor (Orenda Aerospace Corporation) and National Defence Headquarters (NDHQ)

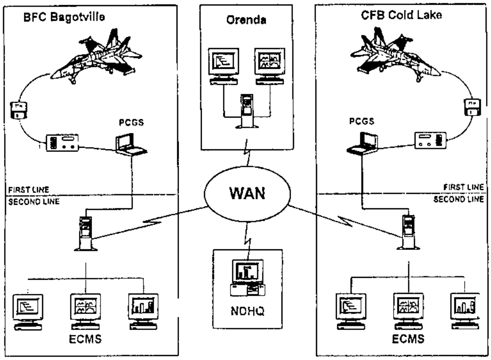

Figure 3 - ECMS Network Configuration

The major elements of the system include:

a. Portable CF-18 Ground Stations (PCGS) located at each squadron;
b. The Base-Level ECMS located at the engine repair section of each base;
c. The Central ECMS located at the 3rd line engine repair and overhaul site; and
d. An NDHQ "Viewer" site.

The functionality of the system at each of these sites is summarized as follows.

Portable CF-18 Ground Station: Each CF-18 is equipped with an on-board Maintenance Data Signal Recording System (MSDRS) which records CF-18 tactical and maintenance data (including the engine IECMS data) to a removal cartridge tape magazine on a continuous and event-triggered basis. The PCGS, which comprises a notebook PC workstation and a specially designed tape reading device (Figure 4), is used to "strip" the data contents of the aircraft cartridge tape and copy these to an Aircraft Data File (ADF) on the notebook. The PCGS software controls the tape reader and provides a number of reporting features for summarizing and displaying the contents of each ADF record block.

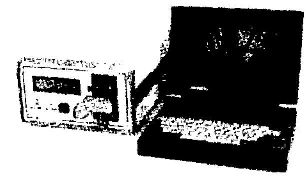

Figure 4 - Portable CF-18 Ground Station

The PCGS software also includes a Flight Line Troubleshooting System (FLTS) feature which uses the IECMS parameter recordings previously described to diagnose engine faults. The FLTS incorporates troubleshooting logic which automatically leads flight line engine technicians through a series of yes/no questions based on the information contained in these recordings (see Figure 5). Over a period of eight years of in-service operations, the Canadian Forces have developed a fault library of over 45 specific F404 engine failure modes and their associated symptoms. Using this library, the FLTS can effectively isolate unserviceable line replaceable items in 60 to 70% of cases, without the need for follow-up troubleshooting ground runs or maintenance test flights.

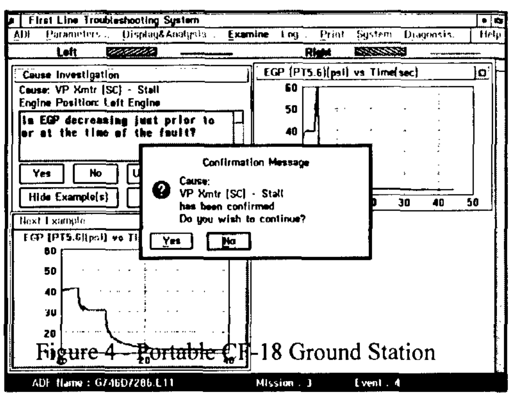

Figure 4 - Portable CF-18 Ground Station

Figure 5 - Flight Line Troubleshooting System

Base Level ECMS: The base level component of the ECMS is used to support the planning and scheduling of second line maintenance; that is, the off-wing repair and replacement of engine components at the base level. The ECMS provides a database of

F404 condition data, including the location, configuration, modification status, life usage history, and maintenance history of all engines resident at the base. Decision support is provided by a number of database application programs as described below.

a. **Maintenance Manager** - To effectively track maintenance information for a modular, field-repairable engine such as the F404, accurate serialized component tracking is required. As shown in Figure 6, the ECMS incorporates a flexible and intuitive graphical tool for this requirement. The various locations where engines and their components are held (operational squadrons, second line repair, serviceable spares, etc.) are represented by individual "windows". Within each window, engine components are represented by a hierarchical "map" of the engine, its modules, assemblies and parts. Configuration changes are made by "dragging" a component from one location and "dropping" it in a compatible location in another assembly or organizational window. Upon the conclusion of a transaction, the appropriate pre-completed maintenance action form is displayed for review and completion by the system user. As well, as each transaction is executed, it is carefully validated using database rules for component attachment compatibility and access restriction. The Maintenance Manager is also used to register modifications (generally resulting in a part number change) and special inspections against specific serialized components as part of the overall configuration management process.

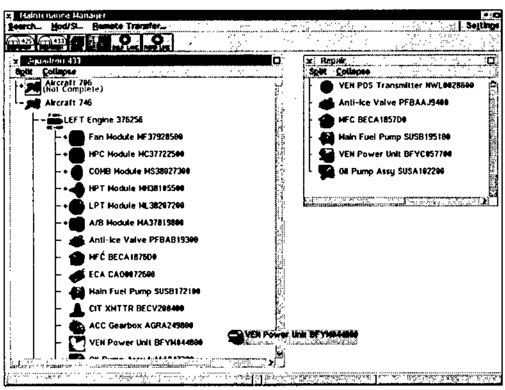

Figure 6 - Maintenance Manager

b. **Life Usage Monitor** - The ECMS tracks the cumulative life usage status of 26 life-limited and 54 logistically critical components of each F404 engine and uses this information to forecast engine shop visits and lifed component replacement requirements. Usage data (in the form of Life Usage Indices computed by the IECMS and downloaded from each TTM tape) are automatically applied to the appropriate aircraft tail number and subsequently, through the configuration tracking features of the system, to each aircraft, engine, module, sub-assembly and part. Historical usage

accumulation rates are then used to project the estimated flying hours remaining on each part and when replacement or maintenance is required (Figure 7).

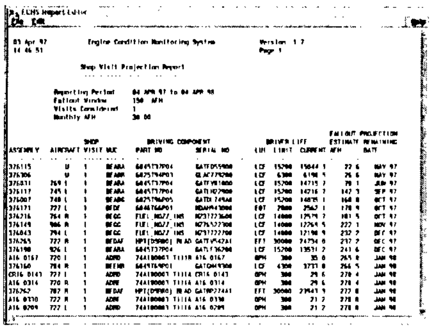

Figure 7 - Shop Visit Rate Forecast

c. **Performance Monitor** - The Canadian Forces have undertaken an extensive research and development program in co-operation with GasTOPS Ltd. to develop a prognostic capability for the F404 engine using data recorded by the IECMS during the ground roll portion of each take-off. These recordings consistently and repeatedly capture the dynamic response of the engine to a slam acceleration from ground idle to takeoff power. From these recordings, the ECMS automatically computes nine "condition indicators", (e.g. rotor acceleration times, N_1/N_2 speed ratio, fuel ratio units and Variable Exhaust Nozzle position) and stores these indicators in the system database against the appropriate engine serial number. The Performance Monitor tool, which is still under development at the time of writing this paper, can graphically display the condition indicator trend plots for a selected engine (Figure 8). The software also incorporates a rule-based expert system to automatically interpret these trends and provide maintenance recommendations.

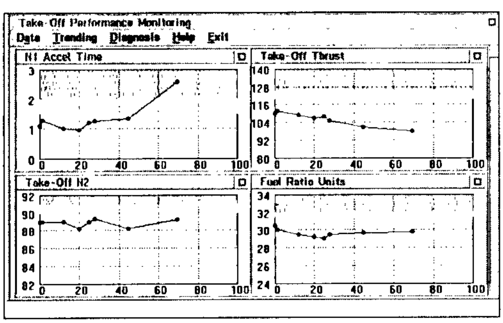

Figure 8 - Trend Plot

Central ECMS: Condition data for the entire CF-18 engine fleet is maintained in a central database at the engine overhaul contractor, Orenda Aerospace Corporation. The central database is updated nightly by data transferred from each of the two main operating bases. Information pertaining to new components are entered into the central database by Orenda as they are received and incorporated into the database. Repair histories and strip reports are also entered into the central database by Orenda.

The central database is used by the F404 Engineering Officer at National Defence Headquarters for fleetwide maintenance management. The most significant aspect of this management support is the planning and scheduling of life limited component removals. The F404 engine, as previously noted, has 26 lifed components, each with a different life limit. Several of these components, such as the HP turbine blades, have long lead times for ordering replacement parts. It is therefore necessary that some form of forecasting tool be available that enables the Engineering Officer to project when lifed components will reach their expiry limits. Moveover, because of the operational impact of the shop visits necessary for component removal, it is often advantageous to remove certain components opportunistically when an engine is in the shop for repair or overhaul anyway. The central ECMS includes a Logistics Planning Model which uses fleetwide historical usage accumulation rates and projected flying rates per mission to forecast the fallout of lifed items and, hence, the requirements for replacement parts. As part of this model, a "window" can be defined whereby parts are opportunistically removed if they will reach their life expiry limit within a specified number of flying hours. By adjusting this window, the Engineering Officer can adjust shop visit rates to match field and depot repair level capabilities and can optimize the material and labour costs associated with lifed component replacement.

The central database also contains the maintenance histories of all CF-18 engines including operational problems which occur in the field, the symptoms associated with these problems and the resolution of the problem in terms of the component or components which were at fault. This information is used by the Engineering Officer to establish priorities for the allocation of resources in support of F404 reliability enhancements, such as turbine blade repairs. As well, whenever an engineering change (e.g. a component modification or maintenance procedures change) is implemented to address a problem, the ECMS provides a means of monitoring the effectiveness of this change. The maintenance histories and failure rate information provided by the ECMS are also being used to quantify the benefits of the ECMS in terms of its impact on the frequency of certain repair activities.

The final major use of the central ECMS database is for ongoing refinement of the ECMS system itself. The central ECMS provides a database for engineering analysis and maintenance methods development. For example, studies have been done which have quantified the effects of mission type and ambient temperature on the usage rates of F404 engine components. This information has, in turn, been used in the Logistics Planning Model to enable more accurate forecasting of life-limited component removals.

Similarly, statistical analysis has been performed to establish reliable alarm levels for F404 performance monitoring and to correlate the performance characteristics of the engine as captured by the IECMS recordings to specific component faults.

Benefits of ECMS: The ECMS is unique amongst Canadian Forces' engine fleets, and is constantly scrutinized for technical and economic performance, both technical and economic. The complexity of aircraft operations and maintenance makes quantifying the benefits of the system challenging. The following sections describe those benefits.

Flight Line Troubleshooting System Benefits: As discussed previously, the FLTS was developed to enable engine technicians to rapidly and accurately diagnose engine faults. The Canadian Forces commissioned a study that was released in October 1994 to determine the annual cost savings realized by the FLTS. The results of this study are discussed briefly below.

The FLTS system has been designed to reduce maintenance costs at all three levels by minimizing false or unnecessary LRU removals and maximizing fault diagnosis/resolution at first line. This is achieved by providing the technicians with a fault diagnosis capability for engine incidents that are caused by a defective LRU or by improper operation of the engine. This diagnosis is only possible if the cause of the unserviceability impacts the performance of the engine and this performance change is recorded by the IECMS system.

In order to quantify the annual cost savings realized by the FLTS, all engine incidents for a two year period (1990-1991) prior to implementation of the FLTS and a one year period (1993) following its implementation were examined. Analysis of the pre- and post-FLTS periods revealed that the system significantly reduced the maintenance activity at all three maintenance levels. For example, the FLTS system resulted in a reduction of LRU removals per incident of 26%, a 50% reduction in false engine removals and a significant reduction in submission of serviceable LRU's to third line for repair (24% for fuel control units, 61% for engine control assemblies). The reduction of assets returned to third line has resulted in a number of additional spares that can be utilized by the CF and these excess spares result in a cost savings when a component is attrited (i.e. an additional component does not have to be purchased when a component is scrapped). The end result of all these cost savings is that the development of the FLTS software showed a pay-back period of approximately 8 months. The Canadian Forces is anticipating that these savings will continue to grow as the system is further automated and refined.

Usage Monitoring Benefits: Traditionally, aircraft engine components and structure were maintained on time-based criteria since measurement and recording of actual stress or life cycle usage was not possible. That is not the case with the CF18, due to the IECMS capability of recording real-time cycles for the F404, which was safe-lifed in those terms. No life is lost in conservative conversion to airframe hours. The Engineering Officer at National Defence Headquarters takes advantage of the ECMS usage monitoring capabilities to ensure that operations are affected neither by exhausted

supplies nor by logistics confusion, due for example to configuration or modification status. The value of an accurate, up-to-date and user-friendly configuration database has been proven many times in the past. This is especially true during times of unexpected component life reductions. For example, in March 1992 the US Navy experienced an uncontained Stage 1 Fan disk failure. Following this incident, the life of this component and its mating blades, disks and shafts were immediately reduced in life by over 1000 engine flying hours. This was totally unexpected and CF was placed in a very difficult logistic situation. To compound the problem, subsequent analysis predicted a safe life well below that of the current field limit. In order to maintain flying operations, the CF initiated a risk management program that was only made possible through the use of a system such as ECMS. ECMS allowed DND to micro-management assets at both operating bases in order to minimize the impact of the life reduction. This process relied heavily on ECMS to provide fallout forecasts, asset inventories, supply schedules and asset recovery from modules with time-expired components for mix/match rebuilds of complete serviceable rotors. Through the use of ECMS, this incident was not responsible for any negative impact on fighter operations.

Conclusions: The CF-18 Engine Condition Monitoring System, developed jointly by the Canadian Forces and Canadian Industry, has enabled the CF to adopt on-condition maintenance practices for the F404-GE-400 engine, with consequent savings in engine life cycle costs and improvements to aircraft availability. The ECMS integrates, in a single database system, the data necessary to support decision making at all levels and all locations of F404 maintenance. The system incorporates unique diagnostic and prognostic methods for F404 fault identification as well as sophisticated logistics planning features for shop visit and spare parts forecasting. Because the ECMS was developed in close co-operation with CF field technicians, the system has proven to be extremely flexible and easy to use.

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Logistics of Industrial Lubrication Oil Reclamation

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Abstract: American industries tend to overlook the alternative of oil reclamation because of our relative affluence, and because it's just been easy to throw oil out. But many factors are changing this situation. And technology now exists to produce reclaimed oil that is equivalent to new oil. Specialists in oil technology say, with only mild exaggeration, that really clean oil can be used and re-used indefinitely. Thus the key to gaining all the benefits of an oil recycling program is the recovery of oil at the source of its use, and closing the recycle loop. And the closer the loop, the less it costs. What are these benefits? Cost savings on buying new oil. Better product quality and production efficiency. Savings in downtime of equipment and in repair and replacement of component parts. Reduction of waste oil disposal, its costs and liabilities.

Key Words: Industrial oil; reclamation; macro analysis; micro analysis; clean oil; recycling; indefinite re-use; savings.

Introduction: America uses roughly two billion gallons of lubricating oil each year. Only about 20 percent of these oils is recycled by American industries. By way of contrast, the Japanese recycle 80 percent of their oils.

Our industries tend to overlook the alternative of oil reclamation because of our relative affluence - and because it's been easy to just throw oil out. But many factors are changing this situation. And technology now exists to produce reclaimed oil, oil which is equivalent to new oil.

Much of this process, this new look at the problems of waste oil disposal and at the benefits of reclamation, involves education of management and of plant maintenance people and machine operators. And it involves a new discipline to eliminate the wasteful habits that often seem second nature to us.

Waste Oil Disposal: Disposing of regular, large quantities of waste oil is a real problem - and will be more of a problem. One of the prime reasons for being concerned about waste oil is the environmental damage that can result from waste disposal. These environmental damages are not part of the cost accounting or record keeping procedures of a firm and don't come to light as a cost of doing business.

Thus, to put a dollar cost figure on these damages is not easy to do.

Here are three ways, among a number of others, in which used oil is an environmental threat - and why federal and state governments are cracking down.

Oils find their way into watercourses. Some of this results from individuals dumping oil into sewers. An undetermined but sizeable amount comes from collectors dumping oil illegally.

Another use of waste oil is for dust control on highways. While these findings are not completely verified, it seems that about 70 percent of this oil apparently leaves the roadway either in dust particles or in water runoff, with a major part of the metal contaminants in the waste oil entering the environment.

Thirdly, airborne pollution. When waste oil is burned, heavy metals in the waste oil, such as lead, are brought into the atmosphere as micro-small particles which are a potential danger to health and the environment.

An industrial plant must confront both the EPA and state regulations in its disposal of oil. If a plant buys 1,000 gallons of new oil each month, the EPA often pokes and prods - "how are you using that oil - where is the waste hauler taking it?"

States have their own regulations, and many of them want to be at least minimum in their codes.

A typical industrial lubricant and its additives will start to deteriorate after being in use in the lubricating process. The dirty oil can cause substantial equipment damage, deterioration in plant equipment, and considerable added cost if maintenance staff do not replace with new oil on the scheduled basis. Unfortunately, there will be the pending waste oil disposal problems facing industries for oil replacement in the equipment. This dilemma has been and is a common problem.

The Outer Loop (Macro Analysis): There are two ways to view this condition of oil use in the industrial plant. We call it Macro Analysis, or the Outer Loop, and Micro Analysis, the Inner Loop.

In Macro Analysis, the whole picture of oil usage in a plant is taken. It goes like this:

Crude oil.
The crude oil goes to a refinery.
From the refinery to an oil distributor who.....
..... Sells to the industrial plant as the end user.
At the plant, the oil first goes into new oil storage, then....
Leaked oil, used oil, in the pit goes to mixed waste oil storage.
From there it is pumped into the tank of the waste hauler truck.

At this point, the waste oil can take one of two courses. One is to an oil re-refining plant in conjunction with an oil additive repackage process. The oil is re-refined, is resold to an oil distributor and makes its way back to further industrial use. Or, the waste disposal company plans the oil for disposal, which offers two options. If the oil is "On-Spec" oil, non-hazardous waste, it is burned and as such can provide both fuel energy, but also potential air pollution by-products. If the oil is "Off-Spec" hazardous waste, it requires special incineration, special waste handling, and deposit in a landfill for residuals.

This movement of used oil is an outer loop. It leaves the plant and moves in a cycle to the re-refiner and back to industrial use. Or it leaves the plant with the waste hauler as custodian and moves through the incineration and landfill route.

So what is happening? The buyer of the new oil uses it once, until it is dirty, then discards it and must buy new oil. But potential problems don't cease as the waste oil moves out the back door.

The Inner Loop (Micro Analysis): It's hard to think of an environmental problem whose solution represents all of these: (1) improve the quality of water, land and air; (2) conserve energy resources; (3) make obvious economic sense to the user; (4) and be so easy to do.

In our Micro-Analysis, we start again with the oil distributor bringing oil to the end user. But after its use in the machinery or equipment, its path changes. Instead of being considered a waste substance, the oil is recovered on-site, goes through a filtration and purification process, is returned to new oil storage and then back to the equipment.

Specialists in oil technology say, with only some exaggeration, that really clean oil can be used and reused forever. Thus the key to gaining all of the aforementioned user benefits is recovery of oil at the source of use, closing the recycle loop. And the closer the loop, the less it costs.

There are two additional means of reducing waste disposal of oil.

The first is employment of an on-site oil cleaning service. This contractor brings to the plant a truck which can include various equipment to meet particular needs. This includes oil purification unit, vacuum distillation, high speed centrifuge, bag filters, cotton filters, a filter cart for different micron ranges.

As we said, this program helps reduce the waste oil disposal problem. But it has some negatives:

Most of the time, this service does not test for additives, thus cannot report on what additives may be missing.
It can bring in cross-contamination with other oils.

It can't segregate oils - for example, cutting oil from hydraulic oil.
It doesn't promote a pro-active maintenance policy for lubricants.

A second service that brings assistance to the plant is a contractor who provides a Total Chemical Reduction and Management Program. By "chemical" here, we mean oils, solvents, soaps - anything that contributes to the waste stream. This service helps the customer use all these types of chemicals efficiently, helps him manage his oil usage. It assists the customer in maintaining a proper inventory of these products and will, if requested, do the purchasing of new oil and other needed chemicals. This contractor does not filter or purify oil, but aids the customer in prudent management of his inventory of chemicals. With the normal maintenance and supervisory personnel not equipped with skills in these areas, he provides a professional approach which can fill a gap in plant operations.

Many industrial oil users follow pro-active practices in maintaining high quality recycled oil. Instead of using the oil until hydraulic problems develop and operating efficiency begins to wane, they have a program of regular testing and analysis of the oil. Many progressive companies use on-line monitoring of their oil with monitoring devices for particle counting positioned within the lubrication plumbing.

Caution must be used in selecting an outside laboratory for oil testing purposes. Some of the problems that can be encountered here:

The lab can accept a sample for which the customer maintenance personnel have not taken from the right sample location, have not monitored the cleanliness of the sample container or possible cross-contamination of the sample itself.

Testing equipment settings and frequency of equipment calibration may vary from lab to lab, even though all are under the same ASTM standards.

The lab technician cannot understand customer's oil problems, namely, oil application, equipment application, oil cleanliness target, the plant environment, and cannot communicate solutions for these problems to the customer.

In recent years, there has been more emphasis on testing of industrial oil because of equipment failure. But a valued side effect of this testing has been the realization that such testing is also important for ensuring production continuity and savings in labor and material costs. Regular testing and analysis of oil makes sense as a pro-active maintenance policy. However, customer is bombarded by test reports that he cannot interpret. So this oil analysis program is of no use and may be a burden, which leads to additional production expense.

Clean Oil - Why Is It Good?: Discussions on the role of industrial oil have been as numerous as the applications of the oils themselves. But not discussed as often is the subject of really clean oil. We have mentioned the responsibilities of the user regarding disposal of waste oil and its ultimate effect on the environment. But what

we also are talking about is the conversion, the transformation, of waste oil scheduled to be disposed of, to recycled oil, cleaned and ready to contribute again to a plant's quality production.

Not every application requires fine filtration of its oil. And thus "clean oil" takes on a different definition according to where it's being used. But, in referring to clean oil, plant managers and engineers have been lowering the threshold of contaminants in their oil. Clean oil today means more than what it did 20 and even 10 years ago.

New oil is accepted as clean oil. But, again, it's a matter of definition. New oil....at what point? As it leaves the refinery, oil is clean. But in its journey to the user's plant equipment, the oil has passed through delivery to the distributor; it's piped from his tanks to his truck tank and then through those hoses to the end user's storage tank. In this process it has picked up contamination, and many plant people who are quality-conscious about their oil have it filtered before it enters the work process.

The values of clean oil, their benefits to the user, are becoming recognized and appreciated by more industrial operations each year. However, the understanding of clean oil and the steps needed to maintain it have not quite kept pace. If a manufacturer wants to run really clean oil, it's a help to him to be aware of all the factors that can raise the level of contaminants in the oil. And there are a number of such factors.

Here's one example:

A plant engineer may say confidently, "We are filtering out particulate of about 3 micron and larger, and we periodically bring in a full supply of new oil." What's really happening is this:

When the oil distribution system is new and is started up with a supply of new, finely filtered oil, oil contamination can be said to be at zero level. At the three month mark, contamination has soared past that acceptable level. The old oil is drained, new oil introduced, but the contamination level of the oil doesn't return to zero because some contamination remains in the equipment oil reservoir.

After another three months, new oil is again brought in, but as <u>its</u> use begins, its contamination level is higher than when the new oil was introduced three months previously, because even more particulate has built up in the reservoir and in the plumbing system. This cycle continues, because the deposit of particulate continues to build up.

When fines of 1 micron and up are filtered out in this situation, the level of contamination rises more slowly. As new oil is brought in, there is still some contamination build-up but it continues at a proportionately lower level with 1-micron substance continuing to be filtered out. A build-up will occur, but at a pace

far slower than at the above rate.

A plant engineer, as said above, may refer to "filtering out 3 micron particulate." Actually, this is a deceptive way to refer to particulate contamination problems - by using micron size rating as a benchmark for a better filter.

The particulate condition of oil is actually measured by ISO code cleanliness standard. This standard uses laser light to count particle in different size at 5 and 15 micron in 100 cc volume. And what we mean by the quality of the filtration is actually the efficiency of the filtration. Filter efficiency is determined by the ratio of the number of particle downstream measurement to number of particle upstream measurement. The quality of the filtration is determined by what is being taken out, and the effectiveness of this activity will vary - for example, cutting oil to hydraulic oil. The same filter efficiency rating will vary upon filtering different types of oil and different oil condition.

We are saying "clean oil - why is it good?" We have stressed the value of recycling and fine filtration of oil at the work place to get away from constant disposal of waste oil, and the problems and responsibilities this incurs. But there is another side to this coin: the positive benefits that constantly clean oil bestows on a quality production process. In a word, clean oil minimizes, usually eliminates, the problem caused in machinery operations by impurities in the oil. We will cite three applications where impurities in the oil affect operations negatively - and how constant maintenance of clean oil handles these problems. The "closed loop," that is, exhibits one of its other major assets: supporting a higher level of production quality.

Hydraulic Oil: Contamination of the fluid used in hydraulic systems is said to contribute wholly or in part to 80 percent of all hydraulic system failures.

Larger contaminant particles, between 5 and 15 micron size, present the more obvious ill effects. But the smaller particulate has the more insidious effect: sluggishness in machine performance and gradual wear on components. Larger particles can block an opening but so can the very small ones in the frequent situations where clearances themselves are small, namely sub-micron to 1 to 5 micron in tolerance.

An example would be these typical critical clearances in fluid system components: gear pump, gear to side plate; 0.5 to 5 microns; piston pump, valve plate to cylinder, 0.5 to 5 microns; servo valve, spool sleeve, 1 to 4 microns; control valve, spool sleeve, 1 to 23 microns; anti-friction bearings, 0.5 micron and up. Clearances in many hydraulic components are very close, 0.5 micron and less.

Another troublesome capability of this ultra-small size particulate is its capacity for gathering, accumulating, or "silting," and its capacity for oxidation, which cannot be filtered out by mechanical means. Silt is the accumulation and bonding of very fine

particles, less than 5 micron in size. Combination of silt, oxidation by-products, and heat in the process in hydraulic oil will cause waxy and gummy residue on valve surface which will cause erratic valve performance. When the gap, for example, between components separated by an oil film is bridged by contaminants, abrasion and wear can take place. Further particles result, and these, by means of silting, can bring about failures.

Manufacturers of precision machine tools continue to tighten their requirements on maintaining of clean hydraulic oil. In the past, it was noted that, though components were made with greater care and quality control, these components often operated erratically or failed. Studies on these conditions indicated that finer filtration was needed. Just as important were the initial and operating levels of contamination.

It is the hidden part of the iceberg that trips up ocean liners, and it's the invisible-to-the-eye contamination that often wrecks fine metalworking systems. A large amount of extremely small particles can lap or sludge precision parts. And, regarding hydraulic oil, they can form the nucleus for joining of non-metallic materials to increase particle size and clog small orifices.

Cutting Oil: Shop people are realizing that longer tool life and higher productivity can result from providing better filtration than what's necessary just to keep chips from passing through to the coolant pump.

The negative effect of fine contamination in cutting oil has a marked bearing on tool performance. Since the separation of the metal takes place just ahead of the cutting edge of the tool, there is a cavity at this point. The liquid coolant applied to the job enters this cavity as well as flooding over the part and the tools, and it performs an essential function here in carrying away the heat generated.

The cutting oil entering this cavity can be contaminated with particles of metal separated from both the chip and the body metal during the cutting action. These particles, mostly only a few microns in size, are coated with cutting oil. Some of them become trapped either between the tool and the work or between the tool and the chip, where they are subjected to extremely heavy loading. The resulting friction causes a rapid temperature rise in the particle, which can become white hot and weld to the tool tip. This is a major cause of cutting edge breakdown. When tests have been carried out on this problem, the removal of these fine particles from the coolant has proved to increase the life of the cutting edge.

One test, for example, was with a multi-spindle machine using various tools and recorded with and without fine filtration of the cutting oil. Tools such as drills, reamers and boring tools were involved in the test. Using fine filtration, the average tool life of drills increased by 209 percent, with increases of 44 to 87 percent on the other tools. These tests were carried out on nine different types of steel components with varying specifications. In a continuation of the procedure, results noted under actual working conditions were found to be as good, and sometimes better, than in

the tests.

On machines that use an abrasive method of removing metal, such as grinding, honing and lapping machines, failure to remove the swarf and abrasive wheel debris will cause a rapid deterioration in surface finish on components. What is not normally realized is the degree to which coolants must be filtered to achieve a given surface finish.

Quenching Oil: At what point does contamination build-up in the oil affect the quenching process?

Filtration has long been accepted as a necessity. But the efficiency of the quenching process, and its maintenance costs, may be affected by a lenient attitude toward the quality of the oil in use. How does minute particulate affect quenching results?

Carbon fines of 1 micron in size and less begin accumulating with the heat build-up in the oil. The initial accumulation of these fines first acts as a speed improver in quenching action. But as the contamination continues to increase, the oil slows down. This occurs for two reasons: (1) the growing amount of contaminants reduces the cooling characteristics of the oil (quench curve); (2) oxidation by-product starts to build up in the oil. The oxidation moves chemically to the carbon fines, the oil grows in viscosity and its quenching speed drops more rapidly. The hardness value from this heat treated process become effective on just the part surface, rather than the piece. Metal becomes brittle and can fail prematurely during use.

Another way of stating this contamination build-up: the high temperature of the oil draws condensation from the air. With this higher moisture, plus the heat, the emulsified water and carbon fines exchange molecules - the so-called "Hydrolysis" effect. The carbon metal fines oxidize and become acid.

The loss of quench capability, though it's a gradual, step-by-step process, proceeds at a different pace depending on shop practices, the working environment, the application, heat, and the maintenance of the oil. One factor that is often overlooked and doesn't get deserved credit - or blame - is the entrance of water from the plant environment into the oil.

Water molecules in the oil expand under heat faster than the oil. In molecular terms, this can be a violent activity. The water, in effect, kicks the oil out and actually can create an unsafe working environment, especially, for example, if this is taking place in a 3,000-gal. reservoir. When the carbon content of the oil is high, the resulting oxidation gradually takes its effect in corrosion of the part, the surface becomes brittle and changes color, and deterioration continues until, as said, specs are altered.

The question for the heat treating engineer has to be "How clean must this fluid be for the process to be done right?" And a second question could be "What will be the

direct effects, and side effects, of quenching oil that is not kept really clean?"

Good Filtration - What Should It Do?: There are, of course, many different types of filtration techniques, and each one has its own place, its own application. To mention just a few: the paper filter; vacuum dehydration - low heat for dehydration, high heat for distillation; the electrostatic filter; the centrifuge, both low and high speed; a filter using combinations of chemical compounds.

But regardless of the technique used, the good filter should have these capabilities:

Capacity for achieving low-micron, even sub-micron filtration, depending on the application and still maintain high dirt holding capacity.
Ability to remove dissolved water.
Will lower acidity (Total Acid Number - TAN) and remove oxidation by-products.
Will not affect additives.
Will meet the filtration demands of the particular job. This should include analysis of the problems encountered on the job so that a customized filtration solution can be provided. It has become recognized that tests originally conducted for environmental reasons now are just as important for ensuring production continuity and quality and cost savings.

Oil Dialysis: Oil dialysis is a new method of off-line filtration which balances oil contamination, oil additives, and based oil in an effort to keep the lubricant in the equipment at its best performance during production. It is an oil purification process, rather than oil filtration process, which is capable of completely removing all types of oil contamination incurred during the manufacturing process.

The oil dialysis unit will continuously flush out and purify the lubricant with multiple passes while equipment is running during production. With this oil dialysis method, contamination has no chance to chemically interact with lubricant and has no effect on equipment performance because contaminants are removed from the lubricating system as they are generated. It pro-actively stops the contamination ingression at the original source. The lubricant in the oil reservoir is never contaminated and never will become waste oil for disposal.

This true oil dialysis or oil purification requires that the system must completely remove three major types of oil contamination at a single pass:

Remove sub-micron particulate with at least 98 percent efficiency during oil purification process. In other words, the system can maintain ISO cleanliness code 12/9 to ISO code 13/10 or NAS class 3 to class 4.
Remove emulsified water down to less than 100 ppm.
Remove oxidation by-products which cause high acidity in Total Acid Number (TAN)
Retain original oil additives that protect equipment.

Typical conventional filtration techniques, such as filter cart, vacuum distillation,

centrifuge cannot be claimed as oil dialysis. They require separate filtration processes. True oil dialysis and oil purification require high levels of filtration technology and professional problem solving technique.

The Need: A Change In Attitude And Discipline: As in all plant procedures and improvements, a change in attitude on the importance of clean oil is required from management to gain these very benefits. The machine operator generally is content if his machine is running and he is not being chastised for being out of spec. He does not consider the oil leaking into the drip pan as being a matter of concern. It is always "thrown out," anyway.

Oddly enough, two outside entities have brought the plant manager to a greater awareness of the importance of clean oil and the minimizing of waste oil disposal. Machine tool manufacturers increasingly are requiring effective filtration of hydraulic oil and, in some cases, are building filtration systems into their machines.

Government, also, usually considered a thorn in the side of industrial operations, is forcing plant management to take a new look at dirty oil and its disposal. Government can't say "do this or that" regarding what is done with waste oil but it can call down penalties for disposal violations. It can be said that government at all levels is demanding that industry re-examine this situation and is forcing us to be efficient.

Management must stress to its personnel a "good housekeeping" attitude, a common sense working attitude. And this is a process of education. With machines working at higher speeds and with quality production being stressed more by customers - and their customers - workers must learn that slowdowns, machine sluggishness, shortened tool life can be caused also by accumulations of fine and silt-sized particles, and that this contamination must be monitored on a sustained basis.

Maintenance personnel must be made aware of the many causes of contamination, air-based and moisture-based as well as solid particulate. They must be instructed and encouraged to practice pre-emptive tactics to ensure a continual supply of clean oil and the minimizing of waste oil.

The plant has options for reclaiming and cleaning used oil: shipping waste oil to re-refining services; on-site reclamation provided by an outside source; and in-house recycling of the oil.

The latter offers an additional two options. Individual filtering and purifying units can service one machine and then be moved to another. Or centralized systems can be installed to service a number of machines at the same time. The Japanese have been using this centralized oil purification system for some time, with quality thus being built into the manufacturing process. A number of machines using the same oil are connected by piping to a central reservoir and purifying system, continually recirculating the oil. This process recovers oil at the source, thus shortening the cycle

of contaminated oil and providing a closed loop.

Top management must be convinced of the importance of reducing waste disposal of oil and of the benefits to themselves of reclaiming and cleaning this oil for reuse. For years, American industry had run on a principle of "if it's running, don't fix it." We must, however, inject some important new disciplines into plant management, go back to fundamentals, keep oil clean, use preventive disciplines, pro-active maintenance.

We have been conditioned to look just a bit beyond the end of our nose at short term benefits instead of at the "big picture," where the benefits come in larger sizes.

Yes, that drip pan has a real message. Hopefully, we will see, take note, and act.

Certification for Condition Monitoring, is there a need?

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Abstract: Certification is the latest buzzword floating around the corporate world. Should the company strive to attain ISO 9000 certification? What about ISO 14000? What about all the maintenance initiatives: TPM, CBM, RCM and other TLA (three letter acronyms)?

Putting together a condition monitoring program requires determining what to do, when to do it, and with what technology. Going on-line, or soliciting information from vendors will give several different answers. Conferences like this one are another source of information, but for someone just getting started, there is a lot of confusion.

Of course, you can hire a "condition monitoring consultant", but how do you know the consultant is truly qualified? If you are a large company, and you want to hire a "condition monitoring expert" yourself, what requirements do you look for?

While some condition monitoring technologies have certification programs, how does the training and testing compare from one vendor to another. When there is no certification available, or existing Non Destructive Testing criteria do not appear to apply, what experience do you look for? Of course, the question of how old the knowledge is might well be asked.

Even with technology certification, there is still no certification for "condition monitoring" per-se. We need to ask if there is a way of training maintenance professionals "condition monitoring" that allows rational decisions to be made by management.

This paper will explore the issue, and while it may provide some preliminary answers, it is primarily designed to provoke discussion and comment within the condition monitoring community.

Keywords: Analysis; acoustic emission; condition monitoring; infrared thermography; proactive maintenance; tribology; vibration.

Introduction: In the last few years, there has been a growing impetus for many businesses to gain ISO 9000 certification. As part of this effort, many of these businesses have decided that their personnel should also gain some level of certification in their profession or craft. Admittedly, this is a vanity move by some organizations, but for many firms, the writing is on the wall that to compete, they have to make improvements in the way they do business, and be able to show that improvement to the world. Increasing global competition makes organizational improvement a necessity, and almost every manager has read articles in professional journals about asset management, equipment availability, working smarter, ad infinitum.

Personnel certification is a very fuzzy area. When you look at the certification programs that are available for condition monitoring technologies, two techniques have multiple certification programs available: vibration and infrared thermography. The only question that tends to get asked by management when the programs are discussed is, how much does it cost. As soon as we move to other technologies such as acoustic emission or tribology, the list of certification programs decreases dramatically.

The content and depth of instruction in the various training and certification programs appears to vary considerably. In most vendor sponsored programs, the course is intimately tied up in the hardware or software the vendor provides. This is not necessarily a bad thing, but it does raise questions about the validity of the training for application with other equipment.

Other questions arise as to the currency of the training and certification. Is there a renewal period? Is the renewal tied specifically to active work in the field? Are the renewal criteria realistic?

What if there is no acceptable certification program available? How does a manager gain confidence in the ability of personnel to make the right decisions based on the information provided by the technology? Perhaps the prime question should be, what is the best technology to use in a given situation?

Role of Standards Organizations: In the last year, the potential need for standards for condition monitoring certification have been raised at the International Organization for Standardization (ISO). It is expected that the matter will be referred to a working group soon for action. The issue has also been raised within several national standardization bodies. In the United States, Infrared Thermography, Acoustic emission and recently, vibration have "knowledge" standards promulgated by the American Society for Nondestructive Testing, Inc. (ASNT). While no formal standard for tribology has been accepted, for most people familiar with the technology, the Joint Oil Analysis Program graduates have a clear advantage. In many areas, this is the de facto standard for tribologists. Unfortunately, it is not possible for civilian organizations to take part in this training directly, and must hire their graduates when they leave the armed forces. Even with the fact that international and national standardization bodies are starting to address the issue of technology "knowledge" certification, There are still issues to be raised.

Role of the user/practitioner: At the end of 1997, a thread started on one of the bulletin boards run by Reliability Magazine® concerning certification for vibration specialists. This thread was one of the longest running and wide ranging on the board. Most of the participants in the discussion were vibration analysts, many in independent practice. Two things emerged from this discussion.

First, certification is not a guarantee of expertise in actual diagnosis, nor is lack of certification an indication of lack of expertise. Second, there was a general feeling that not all certification is created equal. This thread is not over, and questions raised by some of the participants asked if there should be certification for other techniques, even proactive techniques such as precision alignment and balancing.

As a maintenance professional, it is incumbent on me to ensure that people hired to perform various condition monitoring tasks are not only properly trained, but competent to do the analysis required in any program. It is also my responsibility to ensure that people receive training updates, that in-house training is properly conducted and that performance of the analysis is properly evaluated. In other words, who provides the guidelines that can be used to ensure that our maintenance program is world class, or even first class?

Unanswered questions: Assuming that a consensus can be reached concerning certification (knowledge) standards for the various technologies, there is no current standard addressing the broader field of condition monitoring, or the integration of technologies. Another area that is open for question is the lack of standards for proactive techniques.

Obviously, it is up to the end user of any condition monitoring technique to determine what is really necessary in the way of training and certification. Many world class maintenance organizations have splendid internal standards and specifications that detail what a given level of worker will know and be able to do. These organizations tend to be those with a long history of condition monitoring involvement. Many smaller organizations have contracted out their condition monitoring and have excellent rapport with, and confidence in, the contract personnel.

While the development of certification standards may not be of significant importance to these organizations, the industry is growing. The competition from outside firms is driving many managers who read the various journals to seriously consider starting a program. As previously asked, where do they start, how do they get the funding for a program when there are no objective standards to present to the budget committee.

For those people who are just starting a program, or wishing to start a program, a standards system would be of immense value. For those practitioners who would like to expand their own business, these standards should be of value.

Conclusions: While I may not have the answers to the questions and concerns raised, I definitely have some opinions about the state of standardization. I am sure that those in the audience have many different opinions. Perhaps if we can get the issue out in the open, we can assist those people who are just starting out in the concept of condition monitoring, and at the same time, help ourselves. This issue will be addressed, sooner rather than later, so now is the time to get involved in the process.

IMPLEMENTING A RELIABILITY CENTERED MAINTENANCE PROGRAM AT NASA'S KENNEDY SPACE CENTER

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Abstract: Maintenance practices have long focused on time based "preventive maintenance" techniques. Components were changed out and parts replaced based on how long they had been in place instead of what condition they were in. A reliability centered maintenance (RCM) program seeks to offer equal or greater reliability at decreased cost by insuring only applicable, effective maintenance is performed and by in large part replacing time based maintenance with condition based maintenance. A significant portion of this program involved introducing non-intrusive technologies, such as vibration analysis, oil analysis and I/R cameras, to an existing labor force and management team.

This paper discusses what is involved in an RCM program and how EG&G is implementing it at Kennedy Space Center on the facilities maintenance program. It discusses technical tools, management tools and people issues involved in achieving the goal of "better, faster, cheaper" in the facilities arena.

Key Words: Maintenance; Metrics; RCM; Reliability

The maintenance program is an integrated, closed loop, continuous improvement process that includes life cycle maintenance planning, asset risk assessment, runtime, calendar & condition based maintenance, outage coordination, facility condition assessment and cost accounting. The maintenance program is proactive in nature, reliability centered and is a true asset management program. Program effectiveness is measured in terms of asset availability, reliability and life cycle cost.

An essential element in the program is the computerized maintenance management system (CMMS) with the capability to interface electronically with subject matter specific software such as predictive maintenance software programs for vibration analysis. The software provides the traditional productivity and maintenance cost reports as well as asset condition and maintenance requirements reports. It generates work orders based on asset condition triggers and time based or usage based preplanned frequencies. The asset inventory, with pertinent data including risk codes and RCM analysis information, is contained in the CMMS. This enables Maintenance Engineers to trend equipment failures for further analysis, and is the means of continually improving the

effectiveness of the assigned levels of maintenance associated with an asset or definable group of assets.

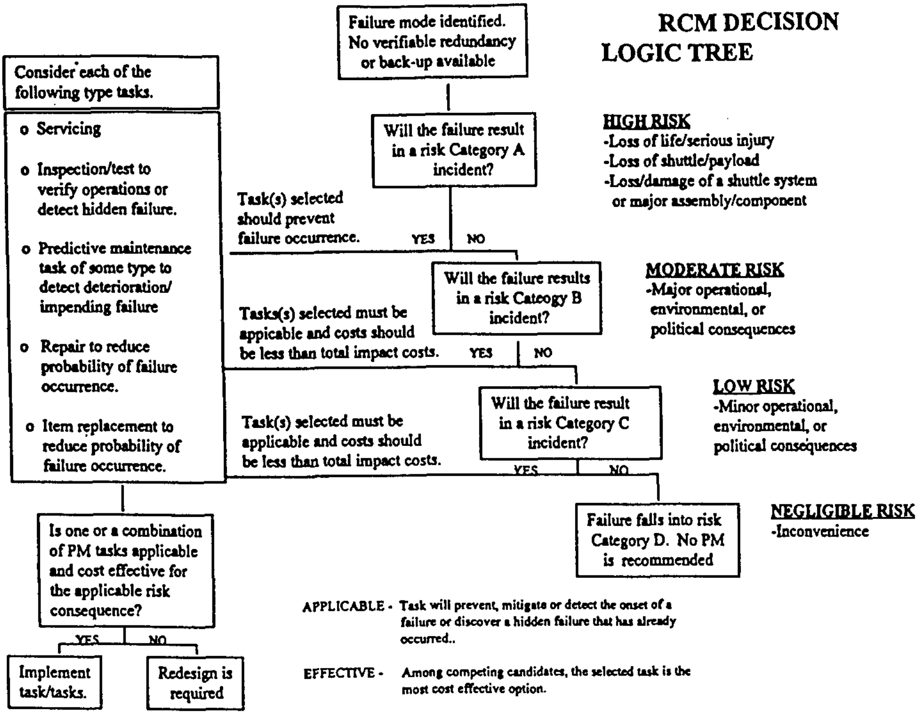
Components The Maintenance Program is a closed loop process that ensures continuous program improvement. The first functional component of the process is an accurate **inventory of assets** included in the maintenance program. It is critical to know **what** is being maintained and have it accurately identified in the CMMS.

Life Cycle Planning ensures the function of the assets is clearly defined, understood and documented and maintenance requirements are planned for the designed life of the asset. This occurs during the design process for new assets and is documented taking into account such things as ease of access to components, minimization of special tooling, incorporation of data for predictive maintenance condition trending, etc. Consideration is also given to the expected life of materials specified in the design and **program maintenance** requirements resulting from expiration of the materials useful life (i.e. repainting structures on a 7-8 year cycle, replacing roofing systems on 20 year cycles, etc.). The more routine recurring maintenance including preventive tasks (service, inspections and minor repair) and predictive testing will be identified utilizing the RCM methodology. For existing assets, this takes place during the RCM analysis.

Once the asset inventory is established and entered into the computerized information system and the function of the individual or defined group of assets is clearly understood and documented a **risk assessment** is performed. The risk assessment of the impact of a loss of function of the asset is performed to determine the appropriate asset risk category Assets fall within four basic risk categories (high, medium, low or negligible) based on the lack of ability to support mission or the cost involved should there be a loss of asset function. This risk assessment is the first step in developing maintenance requirements under an RCM methodology.

A significant component of the program in terms of cost effectiveness is the methodology for determining maintenance requirements. The RCM philosophy is a departure from traditional methods of determining maintenance requirements. RCM logically incorporates the most effective mix of **reactive**, **preventive**, **predictive** and **proactive** maintenance practices and draws on their respective strengths. RCM applies the four maintenance practices where each is most appropriate based on the consequences of failure and the resulting impact to mission. This combination produces optimum reliability at minimum maintenance cost and the combined benefits far exceed those resulting from using any one maintenance practice. RCM incorporates the principle that any maintenance task performed must be proven to be applicable and effective. Applicable implies that, of the competing tasks, the selected task is the most cost effective option. Effective means that the performance of the task will prevent, mitigate or detect the onset of a failure or discover a hidden failure that has already occurred.

During an RCM analysis, engineers use a decision logic tree to assign the proper mix of maintenance. Figure 1.



This decision logic tree focuses on sustaining the reliability of assets in support of a defined mission. The RCM analysis is structured to implement the principle that no maintenance task will be performed unless it is justified. The criteria for justification are safety, reliability and cost effectiveness in deferring or preventing a specific failure mode. Because RCM is reliability based, statistical analysis and conditional probabilities of failure are important in determining the consequences of failure. The primary objective is to maintain the inherent reliability designed into the asset. The product of the RCM analysis is work procedures for both preventive and predictive maintenance that are captured in the CMMS. The performance schedule is also generated in the CMMS as a basis for initiating preventive/predictive maintenance.

The next program component, **Facility Condition Assessment (FCA)**, is important to maintenance engineers and managers as it provides feedback on asset maintenance effectiveness. The FCA is an asset inspection and engineering analysis of maintenance history, failure trends, any root cause failure analysis that might have been performed and any open or planned work requirements. The purpose of the FCA is to validate

maintenance requirements identified during life cycle planning, review and revise the effectiveness of the assigned mix of predictive, preventive and reactive maintenance, identify any new asset deficiencies that may have been detected during the assessment process, review planned maintenance work and review energy issues, if applicable.

Another important part of the FCA is validating the mission of the asset. Program requirements changes many times drive asset mission changes. When mission changes occur, the level of assigned maintenance may require adjustment due to changes in asset criticality. We perform FCAs on a five year cycle to coincide with the budget cycle. Knowing the asset mission, the asset maintenance history, the identified and planned maintenance requirements and the current condition of the asset, work can be prioritized and programmed for performance over the budget cycle. Existing maintenance procedures can be validated and adjusted as required, monitoring programs implemented and tests conducted on assets to further evaluate any suspected problems. The FCA provides a structured process for validating, justifying and prioritizing maintenance requirements.

An appropriate level of maintenance can not be assigned to an asset unless the consequences of failure of that asset are clearly understood. RCM forces focus on the product of a **system**, rather then on individual items within a system. As a result, many items which are critical to a system operation are found to have backups or work-arounds designed into the system, so a failure or loss of an individual item does <u>not</u> result in a system failure. An example of this may be in electric power distribution, where power to a specific facility is critical. The loss of the feeder cable will result in no power <u>through that cable.</u> It will not result in a power loss to the facility, however, because the facility has duel power feed from independent circuits, an emergency backup generator <u>and</u> an UPS. The <u>system</u> does not fail, only the <u>component</u>.

Risk assessment is the first step in determining maintenance levels. Four risk levels have been established, based on the consequences of failure; high, medium, low and no risk. High and medium risk codes are often associated with catastrophic failures, but because of the economic impact costs smaller failures can also fall into this area. If a facility suffers a loss of utilities and has no secondary feed (either onsite or portable), the people in that building will have to stop work and leave. This "impact cost", different from a repair cost, while not obvious to maintainers is real and must be a factor in evaluating the risk level. The RCM analysis is structured to implement the principle that no maintenance task will be performed unless it can be justified. The criteria for justification are **safety, reliability, and cost effectiveness** in deferring or preventing a specific failure mode. Because RCM is reliability based, statistical analysis and conditional probabilities of failures are important in determining the consequences of failure. The primary objective is to maintain the inherent reliability designed into the equipment. Figure 2 graphically ties all the parts together.

INTEGRATED MAINTENANCE PROGRAM MODEL

|—— **100 YEARS** ——————————————||————|

DESIGN /
CONSTRUCT
ACTIVATE < REFURB. > <REPLACE >

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< > PROGRAMMED - ROOF REFURBISHMENT
- EXTERIOR STRUCTURE PAINTING

\+ PREDICTIVE -THERMOGRAPHY ON PWR PANELS
-AND THE ROOF
- VIBRATION DATA ON PUMPS

* PREVENTIVE - A/C FILTER REPLACEMENT

? RUN TO FAILURE - RESTROOM EXHAUST FANS

O CONDITION ASSESSMENT - FACILITIES / SYSTEMS / EQUIPMENT

Figure 2

In this model, it has been determined during the design that the facility is expected to support its defined function for 100 years. The roof of the facility, given the climate the facility will be subjected to, will require major refurbishment after approximately 20 years of service. Therefore, as part of the life-cycle plan, a major refurbishment is identified 20 years from date of facility activation. In addition, while determining the exterior paint specifications, historical data and engineering studies indicate facilities require repainting every five years. This, too, is added to the life-cycle plan as identified program level maintenance requirements. Infrared thermography is also identified on a frequent basis. It is used to perform a condition assessment of the roof and the electrical panels throughout the facility in lieu of previously assigned labor intensive PM tasks. Air filters are replaced on a regularly scheduled basis.

Predictive Maintenance, also known as Predictive Testing and Inspection (PT&I), can determine the condition of the equipment and provide various trend indicators. Interpretation of these indicators allows potential functional failure to be forecast so corrective maintenance can be performed to preclude failure. Working as a complement to the PM program a PT&I program can:

- o Help determine the condition of a component and identify required repairs before that component fails.
- o Conserve resources by performing maintenance on an as-required basis rather than on a calendar frequency or a run-time basis.
- o Minimize down time.

The effectiveness of each applicable PT&I test is examined to determine which test or combination of tests will be used. Any test by itself may not give a good representation of the overall condition of each piece of equipment on the system. However, certain combinations will give a very good indication of equipment condition. Comparisons with previous tests provides trend data useful in condition assessment analysis.

Historically, the focus of maintenance has been the Preventive Maintenance (PM) program. Electrical and mechanical equipment experience deterioration over time that eventually causes it to fail. PM is used to slow this deterioration, ensuring the equipment's operational life. A properly conducted program reduces overall operating costs, aids mission effectiveness, safety, and assures the continued preservation, usefulness, and performance of assets. The PM program, coupled with the other elements of the overall maintenance program, allows engineers to be aware of equipment condition so that sufficient time is available for the systematic planning and scheduling of required repair work.

Preventive maintenance consists of the planned and scheduled maintenance tasks that are periodically performed on equipment to avoid a breakdown. The frequency is based on calendar date, rate of utilization (routine), or condition which is determined by trending data collected through the application of PT&I technologies. The PM program consists of the following:

o Inspections of mechanical, electrical and other physical structures, installed equipment and systems such as motors, pumps, compressors, faucets, light switches, etc.

o Inspections are performed on a periodic, pre-determined basis in aneffort to determine the degree of operating efficiency and whether equipment deficiencies exist.

o Routine servicing of equipment including lubrication, cleaning and changing filters, minor adjustments and parts replacement, and condition reporting.

o Formalized evaluation and work generation system which ensures discovered , uncorrected deficiencies are entered into the normal planning and scheduling system.

Run-to-failure is a reactive component because it is based on the premise that no maintenance task that improves the reliability of the F/S/E in a cost effective manner has been identified. Users call a trouble desk to report breakdowns on run-to-failure items. When the corrective action required is beyond the scope of a trouble call, if engineering is required, or if material must be ordered, the trouble call is changed to a repair work order. As with other work orders, labor, materials and material costs are tracked in a CMMS. This information is then sent to a computer history file which can be retrieved later for use in F/S/E condition assessments, making repair/replace decisions, failure trending, and other engineering analysis.

Maintenance Effectiveness The effectiveness of the maintenance program must be measured and validated. Long term effectiveness is monitored through the facility condition assessment while short term effectiveness is determined using failure trending analysis, which highlights failure trends on like equipment. This advanced notice gives time to take action to prevent catastrophic failures.

Failure trending codes are developed by maintenance engineers with support from field technicians. These codes are used by the technicians in the field to track and classify failures and are recorded in the CMMS. The coding structure, coupled with existing report filter capabilities, allows a relatively quick analysis of failure data. If a problem is suspected, a more detailed analysis is performed. Reports provide information on the following elements: 1) number of loss-of-function events; 2) cause of loss; 3) disposition of cause; and 4) corrective action taken.

PROGRAM MEASUREMENTS (METRICS) The following metrics are reported to measure the progress and of cost effectiveness of the maintenance program.

a. ***Equipment Availability***

$$\% = \frac{\text{Hours System/Equipment is Available to Run at Capacity}}{\text{Total Hours During the Reporting Time Period}}$$

b. ***Maintenance Overtime Percentage***

$$\% = \frac{\text{Total Maintenance Overtime Hours During Period}}{\text{Total Regular Maintenance Hours During Period}}$$

c. ***Percent of Emergency Work to Routine Work***

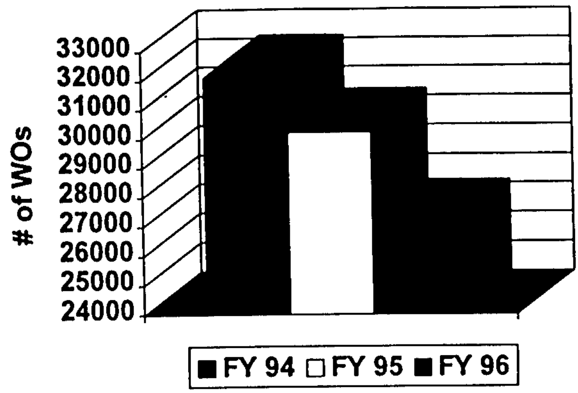
$$\% = \frac{\text{Total Emergency Hours}}{\text{Total Maintenance Hours}}$$

d. *Percent of Faults Found in Thermographic Survey*

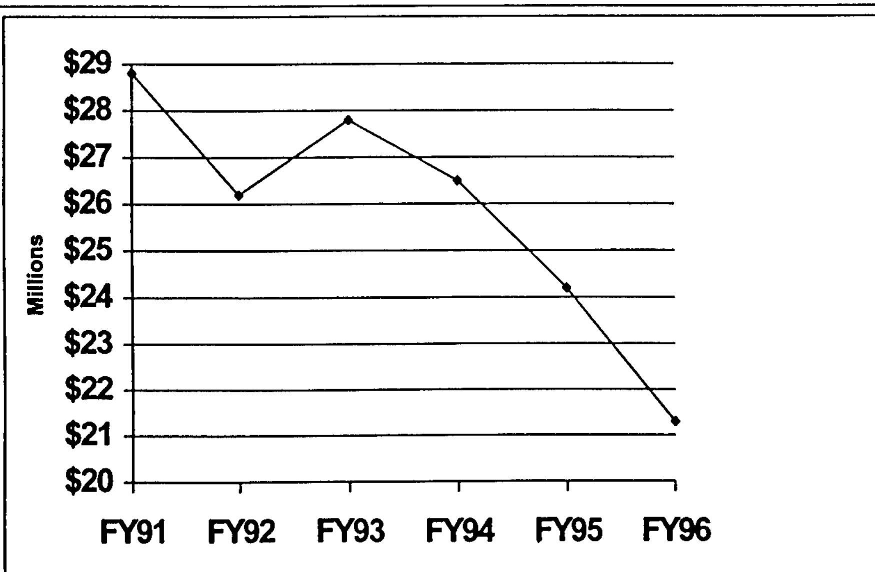
$$\% = \frac{\text{Number of Faults Found}}{\text{Number of Devices Surveyed}}$$

e. *Total cost of maintenance per year*

Figure 3 shows some results obtained by the program as measured by two metrics.



ACTUAL MAINTENANCE COSTS



Lessons Learned Many of the lessons we learned are available from existing texts, both technical and management. It is perhaps inevitable that lessons have to be learned individually in order to be understood, and so many of the lessons presented here are of an obvious nature. By far our biggest finding was the value of repetition. By definition, a cycle of continuous improvement implies doing the same thing over and over and getting a bit better each time. Implementing a reliability centered maintenance program involves changing the way people think and work. Training, explanations, briefings, analysis, making changes and tracking results were done on an individual basis, shop by shop. Selecting a visible, intuitive initial technology is also an important point. Laser alignment was easily demonstrated, learned and understood; vibration monitoring is more involved and less readily grasped. I/R cameras are so advanced the operation is simple; point and shoot technology allows anyone to actually see the temperature difference between a loose connection and a proper one. As we were able to show results, we began to build a cadre of supporters who functioned as champions in their own right.

When we began this project, we went through a developmental phase, an implementation phase and are now in an operational mode. It is no longer a phase - we have achieved a shift in the way we do business. The very nature of the process ensures it will repeat itself over and over - a cycle of continuous improvement. This program is not something we do - it is a way of getting things done in an efficient, cost effective and risk appropriate manner.

Acknowledgments

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Adaptive Trend Analysis - A Simple Solution to Data Variability

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Abstract: *This paper discusses variability problems with oil test data. Simple adaptive trend algorithms can be used to reduce the effect of data variability (from sampling, testing & related maintenance procedures) on trend analysis. The method described reduces the uncertainty in sample interpretation results. Examples are used to emphasize key points.*

Oil Data Variability: Making a reliable recommendation with specific maintenance instructions from routine sample data is a necessary requirement for a condition monitoring program. However, reliable interpretation is often difficult because of a normally high variability in sample data. Trend calculations are easily compromised by maintenance, sampling and testing procedures. The following are examples of the more common problems with associated general purpose solutions, which can dramatically improve data trending reliability.

Effect of High and Low Readers: The nominal test readings from two machines of the same type, operating in the same environment are usually different. Sample readings usually range from a nominal low value to a nominal high value requiring different baselines for trend line analysis for the individual machines. Consider the wear trends shown in Figure 1, the readings of the first four samples (Equipment A and Equipment B) show the typical nominal range. When using simple condemning alarms, the same increase in the wear rate would be interpreted differently for Equipment A then for Equipment B.

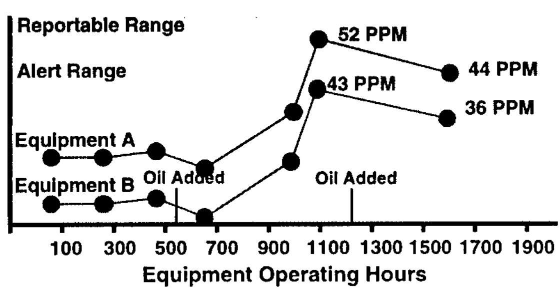

Figure 1: Trends of Similar Equipment in Same Service

Few oil analysts would misinterpret the data shown in Figure 1, but in the real world, single machine data is not comparatively displayed with idealized data or data from other machines from the same equipment family. The dependence on simple limits often results in misinterpretation.

Effect of Data Measurement Variability: Consider the spectrometric data presented in Figure 2. This table shows statistics calculated from six successive weeks of sample data (~4500 samples) generated by a rotary disk emission (RDE) spectrometer from a fleet of 1500 diesel engines; followed by an additional six successive weeks of sample data (~4500 samples), from the same fleet, generated by an inductively coupled plasma (ICP) spectrometer.

RDE Spectrometer	Pb	Cu	Sn	Fe	Cr	Al	B	Na	Si
Average:	16.2	20.1	2.0	32.0	8.5	4.3	5.2	27.2	8.9
Standard Deviation:	5.5	4.3	1.7	5.7	4.0	1.8	5.4	19.8	4.1
ICP Spectrometer									
Average:	5.0	8.0	1.1	15.9	1.5	2.4	2.4	17.8	6.5
Standard Deviation:	2.8	2.4	0.9	4.2	1.5	0.5	2.6	16.3	2.9

Figure 2: Differences between Tests on the Same Equipment Fleet (~4500 Samples)

Note the very large differences in readings between the RDE and ICP instruments! Different oil laboratories may use different instruments, and larger labs may have several different instrument models. Do you know which instrument type your samples were analyzed on? Or, if samples are always analyzed on the same instrument? Samples analyzed on different instruments often give different results, even when the instrument is of the same type, but of different manufacturer—this is particularly true if the instruments are not enrolled in a correlation program. Nor is the problem limited to spectroscopy, oil physical property measurements can vary significantly from instrument to instrument and operator to operator using the same instrument! In addition, many of the common oil property tests are operator sensitive and different technicians often generate different results.

Effect of Maintenance and Sampling Practice: Consider the trend plot shown in Figure 3. The last two samples (**A1 & A2**) were taken at intervals longer than the specified sample interval. When this happens, the data lost often masks the effect of maintenance activities and reduces potential warning time available to plan a maintenance response in the event the last sample is abnormal. The second last sample (**A1**) does not indicate the high rate of change (trend slope) that would have been indicated if sample **C** was taken at 1350 hours. Nor does it indicate the actual effect of the oil addition (1400 hours) that would have been indicated by the missed sample (**D**) at 1500 hours. The long interval for the last sample (**A2**) further reduced the effective rate of change indication and although it results in an alarm, significant warning time was lost. The missed sample **E** (1650 hours) would have restored some indication that a high trend was present, however the combination of all missed samples (**C, D & E**) in conjunction with the oil addition at 1400 hours effectively eliminated usable trend history until the last sample (**A2**).

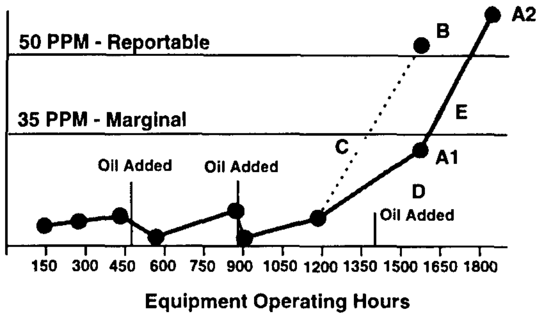

Figure 3: Effect of Long Sample Intervals

Note, had the samples at 1350 & 1500 hours (**C & B**) been taken on time and the oil not added at 1400 hours, the warning trend would have occurred over 300 hours earlier.

Oil Data Interpretation Solutions: The most important solution for data variability due to sampling, testing or maintenance procedures is to provide *management oversight to ensure all procedures are carried out properly.* While different corporate departments and/or commercial contractors make the task of quality assurance difficult to manage; accepted certification standards, such as ISO 9002, can be applied to obtain effective results.

The second most important factor in oil data variability is the proper scheduling of sampling and oil related equipment maintenance. For example, samples taken after an oil change provide a good indication that the oil was changed but no indication of oil or machine condition—that data was disposed of with the oil. Oil, filter and component changes should be scheduled after sampling to preserve condition history. The exception to this rule occurs when the oil change and sample interval are equal. The data from a sample taken just prior to oil drain will always show the oil at the end of its usable life—a fact already apparent by scheduled oil change—unless the oil is being changed prematurely. When the optimum sample interval is effectively equal to the oil change interval, the actual sample interval should be set to get at least two samples per oil charge. One at about 30% to 50% of the oil drain interval and the other just prior to drain. Data from these two sample points and new oil samples will significantly improve trend analysis results.

After sampling, testing and maintenance procedures are improved to the extent possible, mathematical data interpretation procedures may be used to reduce the effect of any remaining data variability. However, some scheduling conflicts will continue to occur and data trending and interpretation procedures must be adaptive to overcome these interferences. An adaptive trend system requires some standards to permit the system to distinguish between normal and abnormal procedures. Normalization can be established

by assigning a standard sample interval for each machine type from which the trends will be calculated. The most appropriate trend equation may be selected in accordance with oil change and sample interval data to determine the most reliable trend data.

Rise over run from previous sample: For routine samples that are taken between one-half and one and one-half (0.5 to 1.5) the standard sample interval—providing the oil has not been changed since the last sample. Figure 4 shows a *rise-over-run* equation which will calculate a reliable trend accounting for the actual equipment usage.

$$Trend = \left(\frac{CS - LS}{AI} \right) * SI$$

CS: current sample data,
LS: last sample data,
AI: actual time-on-oil since the last sample, and;
SI: established interval for equipment type.

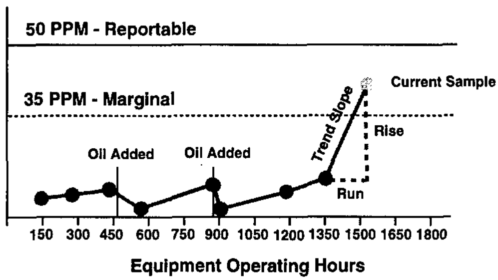

Figure 4: Rise over Run Calculation

Rise over run from a statistically derived historical point: If the sample *interval is smaller than 0.5 times the standard interval* and there are sufficient samples, use a linear regression to predict the value of a sample one standard interval prior the current sample. Likewise, if the sample *interval is greater than 1.5 times the standard interval* and there are sufficient samples, use a linear regression to predict the value of a sample one standard interval prior the current sample. Trend data can then be calculated by a rise-over-run equation using the predicted sample and current sample data.

$$Trend = \left(\frac{CS - PS}{SI} \right) * SI$$

CS: current sample data,
PS: predicted last sample data, and;
SI: established interval for equipment type.

While more sophisticated nonlinear or curve fitting techniques can be used, the author has found this method to be satisfactory for automated oil analysis trending. In Figure 5, note the difference in trend slope for the predicted last sample versus the trend slope from the actual last sample. Long sample intervals tend to reduce trend values and alarm indications.

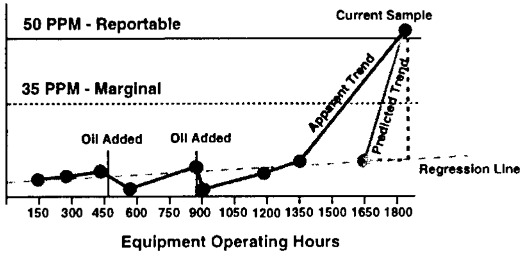

Figure 5: Calculating Trends from a Predicted Last Sample

Short sample intervals, such as occurs when check samples are taken (Figure 6), can effectively destroy the actual trend because of the short interval involved. Again, a regression line can be used to predict a reasonable last sample value, dramatically improving the rise over run trend calculation.

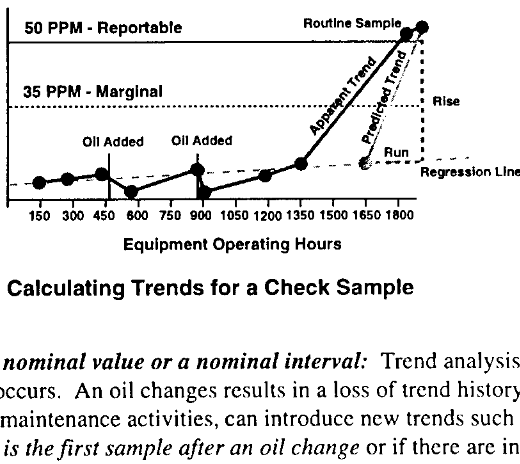

Figure 6: Calculating Trends for a Check Sample

Rise over run from nominal value or a nominal interval: Trend analysis works well until an oil change occurs. An oil changes results in a loss of trend history and when associated by other maintenance activities, can introduce new trends such as break-in wear. *If the sample is the first sample after an oil change* or if there are insufficient samples since the last oil change to perform the linear regression calculation, calculate the trend using a *rise-over-run* equation and the time-on-oil.

$$Trend = \left(\frac{CS - Avg}{OI}\right) * SI$$

CS: current sample data,
Avg: Average of first samples after oil change,
OI: actual time on oil, and;
SI: established interval for equipment type.

Since there is no prior sample, the average data of all samples taken immediately after oil changes for this equipment type can be used to provide the missing last sample data. Alternatively, if the history prior to the oil change shows an abnormal trend, the trend data occurring before the oil change may be used to estimate or predict the trend which

should follow the oil change. Remember, destroyed trend data can never be recovered and oil change maintenance should always be scheduled with oil analysis in mind. The plot in Figure 7 shows the difference between the slope of the actual measured trend versus the slope of the predicted trend. When an abnormal condition is masked by an oil change, the data often looks like only a small amount of oil was added (Apparent Trend). In reality, the slope of the predicted trend indicates the abnormal condition has worsened, while the apparent trend slope suggests the situation is improving. While current sample data has not exceeded the established alarm, action may be required as the lost data cannot be made up without accurate knowledge of oil system additions. In most cases, trend data is more significant then level alarms.

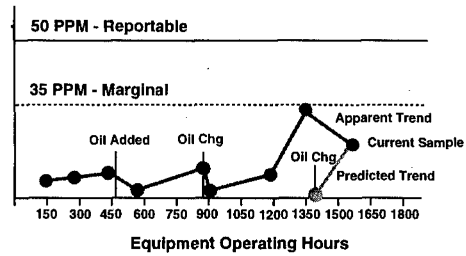

Figure 7: Calculating Trends after an Oil Change

Conclusion: Due to variability of oil test data, some form of adaptive trending is necessary for reliable condition monitoring. In addition, mathematical trending algorithms can become quite complex unless some standard method is devised. Analysis of railway, maritime and other machinery oil analysis programs has determined the above trend equations and procedures are effective at compensating for oil data variations caused by most operational and maintenance events. In these industries, autonomous oil analysis expert systems have been developed and implemented, confirming the stability and reliability of the procedures used.

Most large equipment operators, have databases with sufficient historical data to determine the critical failure modes and their indicators; reliable alarm limits; operational and maintenance events that affect data integrity or reliability; and the appropriate maintenance responses for each failure mode. With a well planned data management system, the interpretation of condition data by mathematical procedures is feasible. Moreover, the approach is consistent, thorough and reliable.

Impact of Test Dust Changes on Particle Size, Particle Count, and Fluid Cleanliness Classes

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Abstract: For several decades, AC Fine Test Dust (ACFTD) has been utilized for a number of purposes in the area of hydraulic and lubrication contamination control. It was used for primary calibration of automatic optical particle counters, utilized in laboratories to measure the particle size distribution of a fluid sample, either on-line or collected from the operating system in a sample bottle. ACFTD is no longer being produced and many standards organizations are now selecting replacement dusts, most notably ISO 12103-A3, for calibration and testing purposes. Because none of the replacement dusts has identical particle size distribution characteristics to ACFTD, all associated test results are somewhat different. This paper presents typical changes found with the new dusts including the impact on automatic particle counter calibration, resultant particle sizes, particle counts, and fluid cleanliness classes and codes defined in fluid cleanliness standards commonly used in the industry. It should be pointed out that, although the particle sizes defined by the new calibration, and hence, fluid cleanliness codes or classes, will be changing, this is an artifact of the measurement, and actual contamination levels in the field will remain the same as before.

Key Words: Fluid cleanliness classes; particle counts; particle counter calibration; AC Fine Test Dust; ISO Medium Test Dust

Introduction: Air Cleaner Fine Test Dust, also called AC Fine Test Dust or ACFTD, originally sold by the AC Spark Plug Division (later the AC Rochester Division) of General Motors Corporation, was manufactured by collecting dust, primarily silica, from a certain area in Arizona then ball milling and classifying it into a consistent particle size distribution including particles sizes from roughly 0-100 μm. Because of the consistent particle size distribution of ACFTD and its irregular particle shape, believed to be more representative of contaminants found in typical hydraulic systems, it was chosen in 1969-1970 for the development of a calibration procedure for automatic, liquid borne, optical particle counters, termed APCs. Automatic particle counters are utilized in laboratories and the field to measure the particle size distribution of a fluid sample, either on-line or collected from the operating system in a sample bottle. The calibration procedure, ISO 4402:1991[1], still in use today by most fluid power laboratories around the world, is based on the average longest chord dimension, measured using optical microscopes. The goal of the APC calibration procedure was to ensure that particle counts obtained with an APC agreed as closely as possible with counts obtained by optical microscopy, the most common method employed to obtain particle counts at that time. This particle size

distribution defined in ISO 4402 and shown graphically in Figure 1 is used to set the electronic threshold levels which define the particle sizes measured in a particle counter.

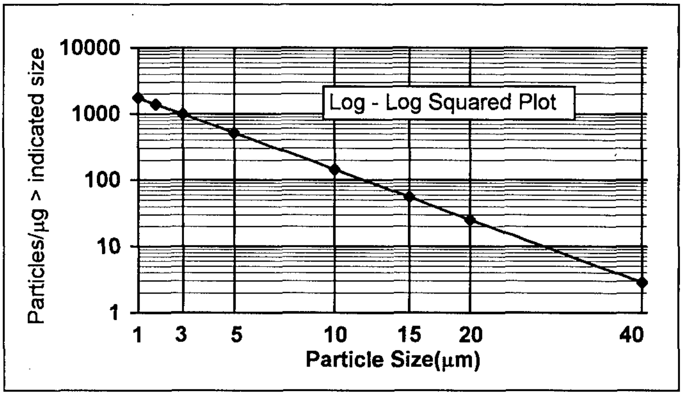

Figure 1. AC Fine Test Dust size distribution based on longest chord dimension.

Since AC Rochester discontinued manufacturing AC Fine Test Dust in 1992, the Society of Automotive Engineers(SAE) in the USA and ISO Technical Committee TC 22 have both made significant efforts to standardize replacement, and additional, test dusts and calibration procedures. Although, at the time of this writing, the modified major test standards have not been officially affirmed, the major portion of the work has been completed. The current status and expected changes are given in the remainder of this paper.

Replacement Test Dusts: The work by SAE and ISO has culminated in the development of a new ISO standard: ISO 12103-1, 1997[2]. This standard defines and designates four new test dusts as listed in Table I.

Table I. Replacement ISO Test Dusts for AC Fine Test Dust.

ISO Designation	Common Name	Other Names
ISO 12103 - A1	ISO Ultrafine Test Dust (ISO UFTD)	PTI 0-10 μm Test Dust
ISO 12103 - A2	ISO Fine Test Dust (ISO FTD)	PTI Fine Test Dust, SAE Fine Test Dust
ISO 12103 - A3	ISO Medium Test Dust (ISO MTD)	PTI 5-80 μm Test Dust, SAE 5-80 μm Test Dust
ISO 12103 - A4	ISO Coarse Test Dust (ISO CTD)	PTI Coarse Test Dust, SAE Coarse Test Dust

The new test dusts are currently being manufactured by Powder Technology Incorporated (PTI) from the same silica based material used by AC Rochester so that the chemical characteristics are similar to the AC Dusts. As opposed to the AC Rochester method, PTI

processes the Arizona dust with a jet mill and classifies it into well-controlled particle size distributions. ISO MTD (ISO 12103 - A3) and ISO FTD (ISO 12103-A2) have the closest particle size distribution to AC Fine Test Dust.

Figure 2 depicts plots of the particle size vs. number distribution of the three dusts in terms of number of particles in one microgram of dust greater than a given particle size. The number of particles in 1 μg of dust is also equal to the number of particles per ml in a 1 mg/L suspension of the dust. The particle size distributions reported in Figure 2 are based on measurements with an automatic particle counter calibrated with ACFTD in accordance with ISO 4402:1991. Neither ISO MTD nor ISO FTD has a particle size vs. number distribution that is equivalent to that of ACFTD. Both ISO MTD and ISO FTD exhibit higher particle counts than ACFTD for sizes below about 10 μm.

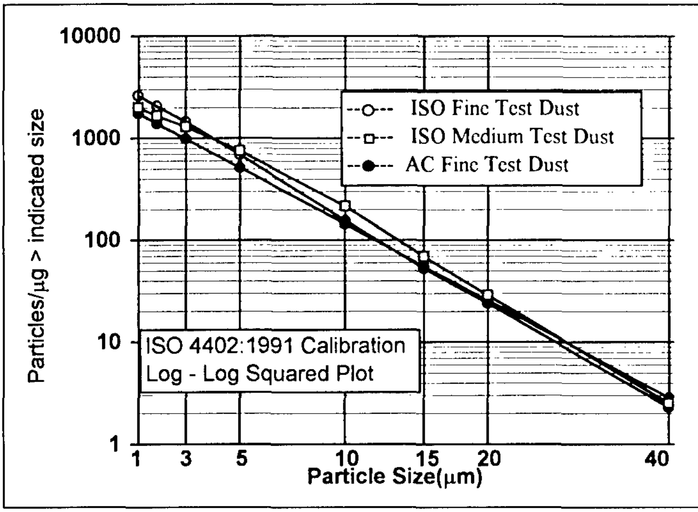

Figure 2. Particle Size *vs* Number Distribution of AC and ISO Test Dusts.

Development of a Revised Calibration Procedure: For some time, the industry had become aware that when more sophisticated instruments such as scanning electron microscopes are used for analysis of ACFTD, a substantial increase in the numbers of particles are reported compared to the distribution based on optical microscopes, given in ISO 4402:1991; this was especially true for particle sizes below about 10 μm. Therefore a project was started at the National Fluid Power Association to develop a new APC calibration method based on a contaminant whose particle size distribution could be traceable to the US National Institute of Standards and Technology (NIST). The result was a new method, ANSI/(NFPA) T2.9.6R1 (1990), that used mono-sized latex particles with sizes traceable to NIST. Usage of this method has been discouraged, since, shortly after its introduction, it was found that poor agreement was obtained between different types of APCs calibrated with latex particles. APCs made by different manufacturers and

APCs utilizing different light sources (such as laser diode or white light) or different measurement principles (light scattering or light extinction) yielded different particle count results when analyzing ACFTD or similar samples. This is due to differences in the optical properties of latex and silica. It was concluded that the APC calibration contaminant should be optically similar to the contaminants typically found in filter testing and field samples.

Based on previous experience, ISO 12103-A3 Test Dust (ISO MTD) was selected as the best candidate due to the fact that it contains less sub-micron particles, which can cause saturation of an automatic particle counter, and is more easily dispersed. A project was undertaken by NIST in 1993 to certify the particle size distribution of suspensions of ISO MTD as a reference material to be used for APC calibration. This effort has resulted in the NIST Standard Reference Material SRM 2806[3] consisting of a 2.8 mg/L suspension of ISO MTD in MIL-H-5606 hydraulic fluid. The results of their analysis show a significant difference in the particle size distribution of ISO MTD as measured with electron microscope (NIST) compared to previous results with an APC calibrated with ACFTD per ISO 4402; see Figure 3. The APC data reported for ISO MTD in Figure 3 are the averages from an international round robin test program sponsored by ISO TC131/SC8/WG9.

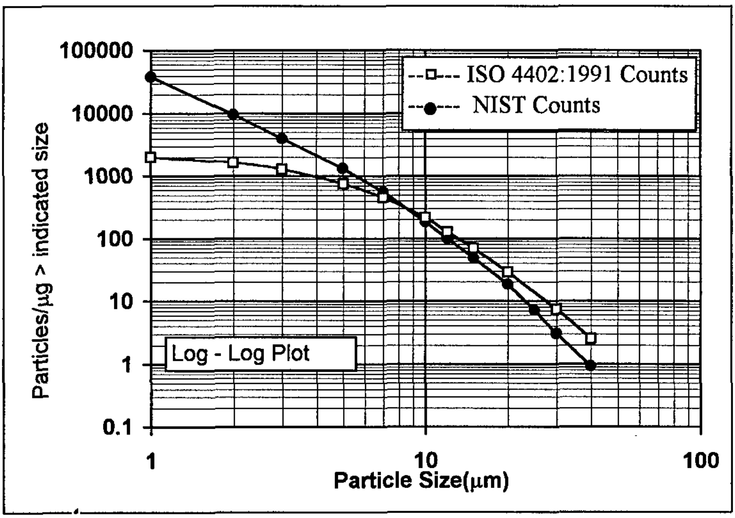

Figure 3. Particle Size *vs* Number Distribution of ISO MTD - ISO 4402 *vs* NIST.

At particle sizes below ~ 10 µm, the NIST size distribution shows significantly higher numbers of particles than the size distribution determined with APCs calibrated per ISO 4402:1991, whereas above a particle size of ~ 10 µm, the NIST distribution shows fewer counts. It should be noted that the NIST measurements were based on the diameter of a sphere whose area is equivalent to the projected two dimensional area of the irregularly

shaped particle; this is the principle of measurement used by most light obscuration automatic particle counters. This differs from the longest chord dimension that ISO 4402:1991 is based upon and is a likely explanation for the discrepancy at particle sizes above ~ 10 µm.

ISO Technical Committee TC131, SC6 has an active project to update the current APC calibration procedure, ISO 4402, using the Standard Reference Material SRM 2806. The revised calibration procedure, circulated for international ballot as DIS 4402:1997[4], includes many other enhancements to ensure better resolution, accuracy, repeatability and reproducibility; however, the effect of the new ISO MTD dust and NIST counts will have the largest impact.

Redefinition of Particle Sizes: Based on the size distributions of ISO MTD in Figure 3, for particle sizes below ~ 10 µm, the particle size determined by NIST for a given particle count (particles/µg) is greater than the corresponding particle size per ISO 4402:1991; the difference increases with decreasing particle size. As an example, the particle count for 1 µm (ISO 4402:1991 calibration) of about 2000 particles/µg corresponds to a particle size of 4.2 µm (NIST size distribution). Thus, below ~ 10 µm, the new definition of the particle size (per NIST size distribution) will be higher than the old definition (ISO 4402), e.g., 2 µm (old) is 4.6 µm (new) and 5 µm (old) is 6.4 µm (new). Above ~ 10 µm, the opposite relationship exists in that new particle sizes will be lower than the old definition, e.g., 15 µm (old) is about 13.6 µm (new). The relationship between particle sizes defined by the ISO 4402:1991 and NIST size distributions for ISO MTD is shown in Figure 4, below, and in Table II.

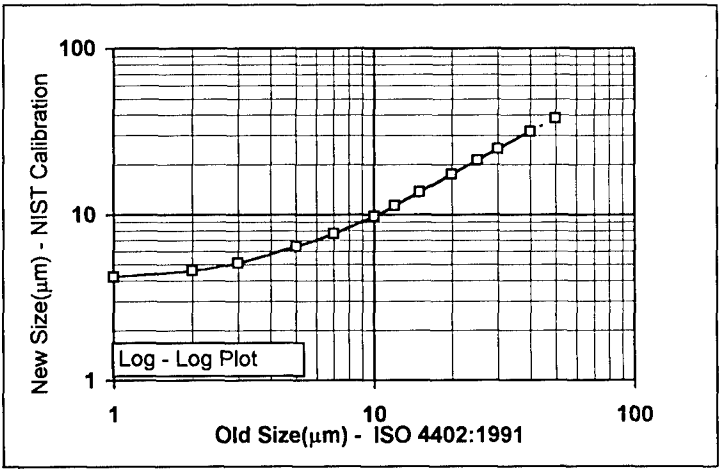

Figure 4. Estimated Changes to Particle Sizes with New Calibration (NIST)

Table II. Comparison of ISO 4402:1991 and NIST Particle Sizes for ISO Medium Test Dust.

ISO 4402:1991 Particle Size(μm):	1	2	3	5	10	15	20	25	40	50
NIST SRM 2806 Particle Size(μm):	4.2	4.6	5.1	6.4	9.8	13.6	17.5	21.2	31.7	38.2*

Extrapolated value; Figure 4.

Note that because of possible differences between particle counters and the accuracy of their original APC calibration, these relationships may vary slightly and must be determined for each APC to be used. It should also be noted that, even though a particle size or count may vary because of the new calibration, the actual contamination level in a system will not be influenced and will remain the same.

Impact of New Calibration on Particle Counts: The particle counts obtained with an APC calibrated with the new procedure will differ from the corresponding particle counts obtained with the APC calibrated per ISO 4402:1991 at any particular size. Users of particle count data must be made aware of the APC calibration method and how to interpret results when using the new method as compared to ISO 4402:1991. As a first approximation, historical particle count data may be converted from ISO 4402:1991 sizes to the new NIST sizes using Table II.

Figure 5 presents the effect of the two calibration procedures on apparent particle count data. As shown in the figure, if one changes from ISO 4402:1991 to the new NIST calibration without making adjustments to the sizes being monitored, significant

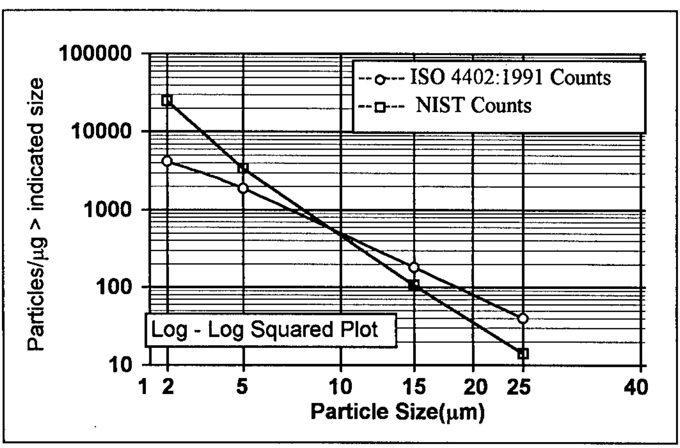

Figure 5. Typical Effect of New Calibration on Particle Counts.

differences arise in particle concentrations. For particle sizes smaller than about 10 μm, apparent increases in particle concentration will be reported which could prompt unnecessary action. The magnitude of the difference increases with decreasing particle size. For sizes larger than 10 μm, the reverse occurs and apparent decreases in concentration result from the new calibration. Failure to recognize this variation as the result of a change in calibration, rather than a change in contamination level, may lead to misinterpretation of particle count data and inappropriate action.

Aerospace Fluid Cleanliness Classification Standards: The NAS 1638 cleanliness standard[5] is comprised of fluid cleanliness classes, each class defined in terms of maximum allowed particle counts for designated particle size ranges. Table III is a partial table of NAS 1638 classes. Cleanliness classes extend from Class 00 to Class 12. For convenience, Classes 3 - 10 have been omitted in the table.

Table III. NAS 1638 Cleanliness Classes.
(Maximum Contamination Limits Based on a 100 mL Sample Size)

Particle Size Range	**Classes**					**Classes**	
(μm)	**00**	**0**	**1**	**2**		**11**	**12**
5 to 15	125	250	500	1000		512,000	1,024,000
15 to 25	22	44	89	178		91,200	182,400
25 to 50	4	8	16	32		16,200	32,400
50 to 100	1	2	3	6		2,880	5,760
Over 100	0	0	1	1		512	1,024

The SAE AS4059 and ISO 11218 Standards [6,7] are derived from the NAS 1638 Standard by: 1) Replacing the differential particle size ranges and particle count limits by cumulative particle size ranges and particle count limits, 2) Extending the lower size range to include a > 2 μm size range, 3) Deleting the 50-100 μm size range and replacing the 100+ μm size range by a 50+ μm size range, and 4) Extending the lower limit of the cleanliness classes to include a 000 Class.

Table IV. SAE AS4059 and ISO 11218 Cleanliness Classes.
(Maximum Contamination Limits Based on a 100 mL Sample Size)

Size	**Class**					**Class**	
(μm)	**000**	**00**	**0**	**1**		**11**	**12**
> 2	164	328	656	1310		1 340 000	2 690 000
> 5	76	152	304	609		623 000	1 250 000
> 15	14	27	54	109		111 000	222 000
> 25	3	5	10	20		19 600	39 200
> 50	1	1	2	4		3 390	6 780

Table IV is a partial table of AS 4059 and ISO 11218 classes. Cleanliness classes extend from Class 000 to Class 12. For convenience, Classes 2 - 10 have been omitted in the table. Unlike NAS 1638, the cleanliness class of a fluid sample is assigned based on the cumulative particle counts corresponding to a specific cumulative particle size range, with the > 5 μm size range being the default particle size range. Other cumulative particle size ranges in Table IV may be specified as the reference particle size range at the discretion of the user.

Impact of New Calibration: As discussed above, particle counts obtained with an APC calibrated with NIST SRM 2806 would be expected to be significantly higher for particle sizes below ~ 10 μm, and somewhat lower for particle sizes above ~ 10 μm, compared to the particle counts determined with ISO 4402:1991 calibration when the same reference size ranges are used with either calibration. Thus, the cleanliness class of the fluid sample would differ from historical data based on ISO 4402:1991 calibration. Since the actual cleanliness level of the sample is unchanged, it would be necessary to change cleanliness level specifications across the industry to compensate for the change in calibration so that actual cleanliness levels remain unchanged, an approach that is considered impractical from the point of view of implementation. In addition, the 2 μm particle size with the NIST calibration is equivalent to much less than the 1 μm particle size based on ISO 4402 calibration (Table II; Figure 4). Most light obscuration type automatic particle counters would not be able to measure this size, as they are typically limited at about 1 μm based on ISO 4402.

In order to implement the new NIST calibration with minimal impact on cleanliness classes, it is proposed to revise the reference particle size ranges in NAS 1638, AS4059 and ISO 11218, based on the particle size relationship in Table II, such that the new particle size range with the NIST calibration is nearly equivalent to the particle size range with ISO 4402:1991 calibration. As an example, 5 μm per ISO 4402:1991 calibration is replaced with 6 μm (6.4 μm rounded to the nearest integer) per NIST calibration. Because optical microscopic particle counting procedures are not being changed, no changes are required in the cleanliness standards provided the size ranges counted correspond to the original size ranges set by the standards. Table V exemplifies the change

Table V. Modification of SAE AS4059 Cleanliness Classes.

Particle Size(μm)		**Class**					**Class**	
Optical Microscope Count	**NIST SRM 2806 Calibration**	**000**	**00**	**0**	**1**		**11**	**12**
> 2	**> 4**	164	328	656	1310		1 340 000	2 690 000
> 5	**> 6**	76	152	304	609		623 000	1 250 000
> 15	**> 14**	14	27	54	109		111 000	222 000
> 25	**> 21**	3	5	10	20		19 600	39 200
> 50	**> 38**	1	1	2	4		3 390	6 780

proposed in the AS4059 cleanliness classes (Table IV) for APC analysis if the approach discussed above is adopted. It should be noted that, since the NIST size distribution does not extend to the 100 μm size range, revision of NAS 1638, as in Table V, would require deletion of the > 100 μm size range and replacement of the 50-100 μm size range with the > 50 μm size range, the same as AS4059 and ISO 11218. The new NIST size ranges for NAS 1638 would then become 6-14 μm, 14-21 μm, 21-38 μm, and > 38 μm.

Industrial Fluid Cleanliness Classification: The ISO Cleanliness Code - ISO 4406[8] is extensively used in the industrial hydraulic and lubrication segment. It is a two number code, e.g., 14/12, based on the number of particles greater than 5 μm and 15 μm respectively. It was expanded to three numbers (ISO DIS 4406, 1994)[9] by the addition of a code number representing the number of particles greater than 2 μm. This standard was approved by international ballot but was subsequently withdrawn prior to publication because of the changes which were imminent to particle size definitions due to the new APC calibration procedure.

The ISO Committee TC131/SC6 has now issued for ballot a modified coding method based on the new calibration procedure. For APC counts, the revised procedure, ISO DIS 4406:1998[10], uses three code numbers, corresponding to the concentrations of particles larger than 4 μm, 6 μm and 14 μm with the new calibration method. The new 6 μm and 14 μm sizes correspond to ISO 4402:1991 sizes of approximately 5 μm and 15 μm (see Table II). These sizes were chosen so that no significant shift in code number occurs due to changes in the APC calibration method. For optical microscopy measurements per SAE ARP598[11] or ISO 4407[12], the calibration is unchanged and the two digits will remain the same as before at 5 μm and 15 μm. Thus the second two digits of the actual code will be similar regardless of the calibration or measurement technique used. The new digit corresponding to 4 μm for APC counts will not be used for microscopic counts.

Conclusion: Replacement contaminant(s) for AC Fine Test Dust, used in the fluid power industry, are necessitated because the dust is no longer being manufactured. In addition, the dust obsolescence as well as a desire to improve APC calibration has resulted in a new calibration procedure that is traceable to NIST. The new NIST calibration procedure will cause numerous changes in the area of contamination control including:

- Particle size definition
- Particle counts
- Cleanliness classes and codes

The projected impact on each of these parameters has been discussed in this paper. Organizations involved in revision of the standards discussed in this paper are aware that there is likely to be a great deal of confusion within the fluid power industry as a result of ACFTD replacement. This is the primary reason that the standards are being revised to minimize changes where possible. Users should always keep in mind that, although laboratory measurements of the particle size distribution in fluid samples (and potentially cleanliness classes) may change with the new calibration, this is an artifact of the

measurement only, and actual contamination levels in the field will remain the same as before.

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[5] NAS 1638 (1992), Cleanliness Requirements of Parts Used in Hydraulics Systems.

[6] SAE AS4059B (1995), Aerospace - Cleanliness Classification for Hydraulic Fluids.

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14 Million Hours of Operational Experience on Phosphate ester Fluids as a Gas Turbine Main Bearing Lubricant.

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Abstract: Phosphate ester fluids have been used as a gas turbine main bearing lubricant for more than 35 years. Acid treatment systems utilizing Fullers' Earth or Activated Alumina have been used to remove acids produced during the PE fluid degradation process on an intermittent or continuous basis. Both acid adsorbing medias contribute metal soaps during the acid adsorbing process. Over time, the build-up of metal soaps significantly reduces the capability of the media to adsorb acids. The end result is escalating acid levels and fluid operating problems.

The introduction of ion exchange as an acid adsorbing media has eliminated the catalytic fluid degradation process, and offers phosphate ester users' extremely long fluid service life.

Key Words: Fullers' Earth, Activated Alumina, Adsorbent, metal soaps, ion exchange.

Introduction: A large gas transmission pipeline has used phosphate ester fluid as a gas turbine main bearing lubricant for over 30 years. Fluid life was generally limited to 4-5 years. Fluid degradation caused numerous turbine and compressor bearing failures. About 20% of the turbine fleet experienced phosphate ester reservoir change-outs yearly. A thorough analytical investigation of 82 gas turbine phosphate ester reservoirs (5000-11000 liters) over a four year period yielded extensive data to redefine existing fluid maintenance procedures. Revised maintenance procedures and the introduction of ion exchange have eliminated bearing failures caused by degraded fluid, and extended fluid life in excess of 230,000 operating hours.

Phosphate ester Maintenance Practices

Prior to 1985, as demonstrated in Figure 1, standard maintenance practice for phosphate ester fluid as recommended by the fluid manufacturer's was to utilize Fullers' Earth media on an intermittent basis to control fluid acid levels between (0.50 and 0.30 TAN).

See Figure 1 (Intermittent acid treatment)

It is not the intention of this paper to discuss the fluid degradation process of phosphate ester fluids in terms of its chemical break-down, as the topic has been documented very well over the years[1]. The major influences on fluid degradation are; system design, introduction of metal soaps, changes in air release time, as well as oxidation and hydrolysis. Key factors contributing to the degradation cycle are shown in Figure 2[2]

See Figure 2 (The Fluid Degradation Cycle)

From a turbine operator's perspective, it is important to understand how the fluid degradation cycle impacts fluid maintenance, fluid health, and turbine operating problems associated with deteriorating fluid. To provide an example from a turbine operators perspective I will describe the fluid maintenance and operating problems of one reservoir that is typical of a gas turbine driven natural gas centrifugal compressor operating at a pressure of 8,000 KPa. Fluid reservoirs for these turbines are from 5,000 to 11,000 litres and would require approximately, 155 Kg. of Fullers' Earth media for fluid treatment.

I will comment on causes of fluid degradation that were established as a result of an extensive review of over-all reservoir health on the entire turbine fleet that was conducted in 1987 with the assistance of both fluid suppliers.

Referring back to Figure 1, we see that by-pass filtration was activated when TAN reached 0.5, and discontinued when TAN was reduced to 0.3. During the 1st year of operation on new fluid, Fullers' Earth cartridges were generally exhausted after two operational cycles through the media over a 3-month period, and four sets of cartridges were used during the first year. Cartridge costs are about 14% of reservoir value. There were no fluid foaming problems or unit operating problems related to fluid degradation.

By the end of the 2nd year fluid life cycle, a set of Fullers' Earth cartridges is exhausted in about 6 weeks. As many as 8 sets of cartridges were used during the 2nd year of fluid operation. Cartridge costs were about 28% of reservoir value. Some reservoirs require small amounts of anti-foam due to fluid foaming.

Here we see the first symptoms of fluid degradation. The 12 sets of Fullers' Earth cartridges that have been used to date to control fluid TAN are contributing sufficient quantities of calcium and magnesium so that fluid air release time is affected. Metal soaps are starting to deposit on the surface of the high pressure oil seals. Calcium and magnesium levels are about 50 to 90 ppm. Reduced seal clearances result in fluctuating seal oil pressure which causes additional foaming of the fluid, along with higher than

normal seal operating temperatures. Acid production rates are increasing due to heat and increased oxidation.

Normal fluid analysis i.e. TAN, viscosity, s.g., and water, would not highlight any fluid problems at this point, however, metals analysis, fluid resistivity, RBOT, and alcor deposition tests would all show signs of early fluid deterioration.

Fullers' Earth adsorbing capabilities are reduced due to fouling of the media with anti-foam, and foam build-up inside the filter housing.

By the end of the 3rd year fluid life cycle, TAN levels have exceeded 0.60, and cartridges are exhausted in 3 weeks. TAN cannot be lowered below 0.50, and cartridge costs are 40% of reservoir value. Anti-foam is frequently required due to significant reservoir foaming and compressor high pressure seal failures that are common. Some turbines are also experiencing "hot" bearings. Calcium and magnesium levels are as high as 300 ppm. There are signs of copper in fluid metals analysis due to corrosive effects of high TAN on copper core oil coolers. Copper is a catalyst in degradation of phosphate ester fluids, but only becomes significant when TAN levels are high.

By the end of the 4th year fluid life cycle, TAN levels have reached 1.9 and Fullers' Earth cartridges are no longer capable of reducing TAN. Cartridge costs are about 56% of reservoir value and compressor high pressure seal failures are yearly. Turbine bearing failures are common before the turbine has reached its 24,000 hour life cycle. Fluid replacement is carried-out in conjunction with the turbine overhaul. Twenty percent of the turbine fleet is experiencing reservoir change-outs yearly. In 1985, Activated Alumina replaced Fullers' Earth as the acid adsorbent media on the turbine fleet.

Figure 3, reveals that even with consistent interrupted maintenance and increasing numbers of cartridge change-outs, the net change in TAN over the 2nd, and 3rd year fluid life cycles is still increasing. By the start of the 4th year of fluid operation, the increase in TAN is very rapid.

See Figure 3 (Average TAN over fluid life cycle-interrupted filtration)

Figure 4[3] helps us better understand why TAN accelerates so rapidly during the 4th year life cycle of the fluid.

See Figure 4 (Oxidative Stability of TBPP)

On reservoirs that had used Activated Alumina as the adsorbent media, severe foaming resulted when sodium levels reached about 90 ppm, indicating that the effects of sodium were much more significant than calcium and magnesium.

The extensive investigation that was carried-out on the turbine fleet also revealed:

- Water did not represent a problem as water levels were all below 200 ppm
- Viscosity changes were minimal
- RBOT tests of new fluid were 200 minutes, and by the 4th year, had reduced to less than 80 minutes
- Total metals content of a 4-year oil reservoir were typically 400 ppm
- IPPP reservoirs had significantly higher total metals and TAN than TBPP reservoirs

While this investigation was on-going, excessive turbine maintenance costs and extensive compression outage lead to a management decision to use mineral oil on turbine packages purchased after 1989.

As a result of the fluid investigation, the following changes were made:

- Continuous fluid filtration was adopted
- IPPP fluids were discontinued, and TBPP was used for fluid make-up
- Maximum TAN of 0.10 was set a new goal.

Over a two-year period it became apparent that the benefits of adopting continuous side-stream filtration was limited to reservoirs in good condition.

While operating on Activated Alumina treatment, it was observed that reservoirs with high metals and high TAN levels, i.e. metals >200 ppm, and TAN > 0.5, exhausted at least 5 times more cartridges than a reservoir with low metals and low TAN, i.e. metals less than 50 ppm and TAN less than 0.10.

One unique reservoir had a TAN of 1.6, with total metals of 40 ppm. This reservoir was brought back to a TAN of 0.10 using three sets of Activated Alumina cartridges. This case suggests that the high metals content experienced in many reservoirs have an impact on the ability of Fullers' Earth or Activated Alumina to adsorb acids.

In 1987, Selexsorb was introduced as an adsorbent media with new reservoir fills. As Selexsorb could not be used on degraded fluid without causing jelling problems, we still lacked a means of controlling TAN on degraded reservoirs.

In 1989, I received some early research that had been carried-out in Europe regarding the use of ion-exchange. After two years of research, I incorporated ion-exchange media into a cartridge format that would fit the existing acid treatment housings used on the pipeline system.

In 1991, ion-exchange was introduced at two Beta test sites in an attempt to rejuvenate reservoirs that had seriously degraded fluid. Reservoir sizes were 5,300 and 11,000 liters respectively.

Both Beta test sites utilized Hilco 6-pack housings using 11 inch by 19 inch cartridges. Initial cartridge configuration used 3 cation and 3 anion cartridges in each housing. Initial metals content of both test sites are shown in Figure 5.

See Figure 5 (Starting Metals Analysis)

Results of Test Site #1:

The first set of cartridges lasted approximately 150 hours. Figure 6, reveals that water content increased from 450 ppm to 1250 ppm, and TAN increased from 0.90 to 1.25. Figure 7, reveals that total metals are reduced from 480 ppm to 110 ppm during the same interval.

See Figure 6 (Tan vs. Water Test Site 1)
See Figure 7 (Tan vs. Metals Reduction Test Site 1)

It is important to note that while the first set of cartridges were in operation, water content peaked at 1250 ppm at 150 operating hours and then dropped back to about 185 ppm. Water evaporated from the main lube oil reservoir and power turbine bearing housing vents. The fourth set of cartridges installed were anion only.

Total metals content at the end of the test was about 50 ppm. Current metals content is less than 10 ppm.

Results of Test Site #2

Figure 8 shows that the first set of cartridges lasted about 48 hours. Metals content decreased from 285 ppm and TAN decreased from 1.15 to 0.75. It is interesting to note that we did not see the high TAN increase associated with cation resin because there were two Hilco housings utilized for this test site. The extra 3 anion cartridges were capable of removing the acids produced from the cation resin reaction.

See Figure 8 (TAN vs. Metals Reduction Test Site 2)

There is some confusion from site personnel as to the make-up of the second and third set of cartridges, however, it is clear that the fourth set of cartridges were anionic as TAN decreases quickly over an 1100 hour time period.

Figure 9 shows the increase in water production. It increases from 300 ppm with the first set of cartridges. Water content during the second and third set of cartridges suggests that the cartridges were not in continuous service. This could have been caused by blockage of the one-half micron post-filter, which was not replaced until the 4th set of cartridges were installed.

See Figure 9 (Tan vs. Water Test Site 2)

At both test sites, the short life of the first set of cartridges was caused by considerable fouling of the media from contaminants being removed from the fluid. Fouling of the half-micron post filter was frequent until the fluid had been brought back to good condition. Typically the first post-filter cartridge reached a differential pressure of 140 kPa within 24 hours, the second within 2-3 days, and the third lasted more than 6 months.

In figure 10, RBOT values for both test sites indicate that fluid recovery was quite significant. RBOT values were brought back to slightly less than 200 minutes.

<u>See Figure 10 (Fluid Recovery-RBOT)</u>

Fluid analysis from test site 1 revealed a "free phenol" content of 8,400 ppm. The second test site revealed a "free phenol" content of 4,300 ppm. This would lead us to conclude that the amount of phenols in the fluid do not impact the over-all health of the fluid or hinder the capabilities of the ion-exchange process.

Figure 11 shows a significant improvement in fluid resistivity after ion-exchange conditioning. Resistivity values increased from 5.6 x 10^9 to 12 x 10^9.

<u>See Figure 11 (Fluid Resistivity Improvement)</u>

To date, over 2,000,000 hours of ion-exchange experience has been achieved on this pipeline system, with TAN levels generally below 0.04. There are occasional "maintenance excursions", where TAN increases to .10, but these are rare and very temporary. Ion-exchange media has proven to have at least twice the life of Selexsorb on the 80 gas turbine packages. I qualify this by saying that Selexsorb used on these reservoirs with a TAN of 0.04 has a life of 6 months. Ion-exchange on an identical reservoir will have a useful life of 12 months.

In my experience, ion-exchange represents the best method of maintaining phosphate ester fluids in "near-new" operating condition. Fluid life can be maintained indefinitely. The youngest reservoir on the turbine system described is about 60,000 operating hours, and the older reservoirs vary from 160,000 to 235,000 operating hours. Figures 12 shows a typical reservoir analysis from a fluid vendor.

<u>See Figure 12 (Typical Fluid Analysis)</u>

Heavy Hydraulic Applications

I have gained considerable experience in the reclamation of phosphate ester fluids used in aircraft elevator lifting systems on Navy aircraft carriers. To date ion exchange treatment has been used on three aircraft carriers, recovering in excess of 50,000 gallons of fluid that was approaching the end of its life cycle. This unique application required an ion-exchange system of sufficient exchange capacity to handle 600 U.S. gallons-per-minute in one pass, unlike a turbine package that is on continuous side-stream filtration at a flow rate of 6 U.S. gallons-per-minute.

The single-pass application provides the means of eliminating any question as to when the media is exhausted. This question has led to significant debate in the by-pass filtration system that is typical of a gas turbine or EHC system. Some period of time elapses before the operator sees an increase in reservoir TAN, and comes to the conclusion that the media is exhausted.

Data from these projects has shown that the initial TAN of the fluid dictates water production. Furthermore, this unique application revealed the significant variation in acid removal rates due to variations in resin water content and fluid viscosity. With "un-dried" resin, total neutralization of the fluid is achieved in one-pass. When using resin from containers that had been opened for a few days, total neutralization did not occur in one-pass. Optimum resin efficiency that has been achieved to date is slightly less than 20% of that expected in the water treatment environment.

In this cold fluid application, vacuum dehydration was required, however, it quickly became apparent that water removal could not be accomplished to acceptable specifications in a single pass. Data from water tests[4] indicate vacuum dehydration efficiency in the order of 65% per-pass. The number of fluid passes required to remove water to specified values became a function of the initial TAN of the fluid being treated. Variations were made in fluid temperature to optimize resin efficiency and minimize pressure-drop across the resin vessels, but higher temperatures proved to reduce efficiency of the vacuum dehydration system.

New Phosphate ester Applications

In 1995, I initiated the development of a phosphate ester fluid to operate in the aero-derivative gas turbine engine environment. My experience in the gas turbine industry had shown that one of the current down-falls associated with the newer "second-generation" gas turbine, i.e. compressor pressure ratios greater than 20:1, was the limitations in thermal capabilities of the polyol ester oils currently being used (MIL-L-23699). A test was initiated for a trial of a TBPP phosphate ester fluid in a General Electric LM 1600 aero-derivative gas turbine. The test was initiated as a result of a number of coking problems associated with MIL-L-23699 oils. The fire properties of the phosphate ester fluid were also viewed as a significant advantage. In my opinion, General Electric has been very proactive by writing a test specification that allows the trial of a phosphate ester fluid in their LM series of gas turbines, LM1600, LM2500, LM5000 and LM6000.

To avoid the issue of water and ion-exchange for fluid maintenance during the fluid trial, Selexsorb was used as the adsorbent media. A standard 7" x 18" cartridge holding ¼ of a cubic foot of media was connected to the lube-oil supply header immediately down-stream of the main lube-oil filters. A post-filter of the same size was installed to insure Selexsorb media did not enter the lube-oil tank.

The test was discontinued due to a compatibility issue with the gas generator oil tank demister element which caused gas generator oil tank pressure differential to be exceeded, however, compatible elements have been procured, and the test will resume in the near future. A proposed phosphate ester trial on a Rolls Royce RB-211G is presently being reviewed between RR and FMC.

I am very optimistic that phosphate ester fluids will provide enhanced fluid performance on the newest second-generation aero-derivative gas turbine engines in operation today.

Conclusions

From a phosphate ester fluid user's perspective, ion-exchange eliminates the catalytic factors that contribute to the degradation process, i.e., metal soaps and air retention when using Fullers' Earth or Activated Alumina. If TAN levels are maintained at "near new " fluid values, the effects of hydrolysis and oxidation are significantly minimized. Ion-exchange offers the *"Total solution"* in the maintenance of phosphate ester fluids as it can rejuvenate degraded fluids, as well as maintain new fluids for an indefinite time.

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[4] Mr. Mark Mosley, Bremerton Naval Shipyard

Figure 1: Interrupted Oil Filtration

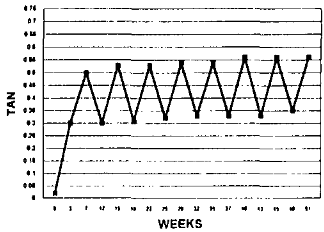

Figure 2: The Fluid Degradation Cycle

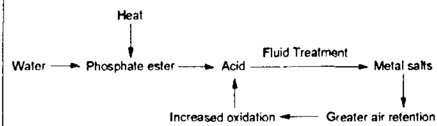

Figure 3: Average TAN over Fluid Life Cycle
Interrupted Filtration

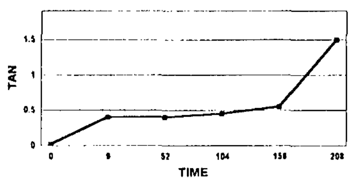

Figure 4: Oxidative Stability

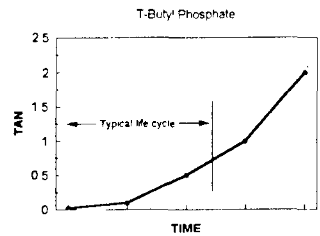

Figure 5: Starting Metals Analysis
Selected Test Sites

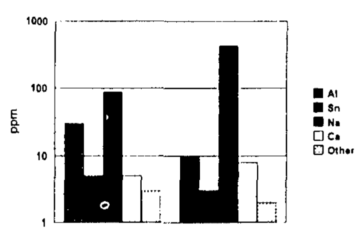

Figure 6: Tan vs. Water
Test Site 1

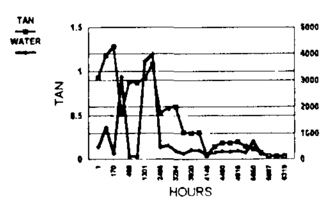

Figure 7: Tan Vs Metals Reduction
Test Site 1

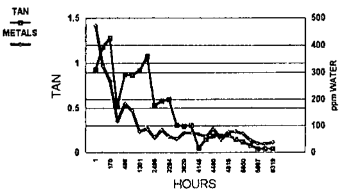

Figure 8: Tan vs. Metals Reduction
Test Site 2

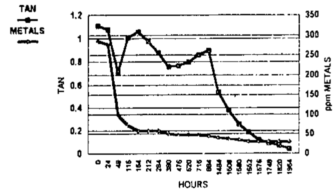

Figure 9: Tan vs. Water
Test Site 2

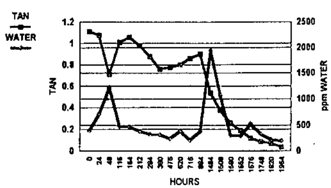

Figure 10: Fluid Recovery
RBOT Comparison

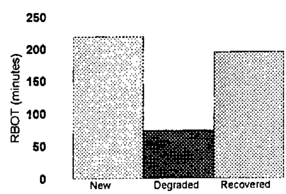

Figure 11: Fluid Recovery
Resistivity Comparison

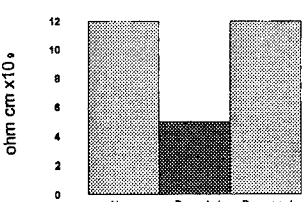

Figure 12: Typical Fluid Analysis

Recommended Limits		Min	Max
Oil Operating Hours	200,000+		
Acidity	0.07		0.10
Viscosity, SUS @100F	169	140	180
Specific Gravity @60F	1.17	1.14	1.18
Water Content WT%	0.01		0.1

Spectrochemical Analysis, ppm (Tested Bi-Annually)

Iron	0	Lead	0
Aluminum	0	Tin	0
Copper	3	Sodium	1
Chromium	0	Magnesium	2
Silicon	0	Zinc	0

TOTAL METALS 6 p.p.m.

Functional Enhancements in Used Oil Analysis Spectrometers

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Abstract: Spark emission spectrometers using the rotating disk electrode (RDE) technique have become the workhorses and primary analytical tool of most machine condition monitoring programs based on oil analysis. This paper describes several new developments that have put new life into this established and well accepted used oil analysis technique. They include performance enhancements, automation and additional capabilities.

Digital technology has been applied in the design of excitation sources, optical and readout systems to greatly improve stability, maintainability and capabilities. A robotics system has also been developed to provide automated and unattended sample introduction and analysis. Several recent new inventions and developments have also augmented the applications and capabilities of the RDE technique. They include, 1.) the ability to analyze large wear particles, 2.) a modification to include the ability to analyze diesel engine coolants and water, 3.) the development of an additional small optical system to make it possible to analyze sulfur in oil and fuel and 4.) a modification to analyze the conductivity of a used oil sample in the same step as the normal wear metal analysis.

Key Words: Oil analysis spectrometers, rotating disk electrode (RDE) spectrometer, automation, solid state excitation, large particle size analysis, coolant analysis, conductivity analysis, sulfur analysis.

Introduction: Oil analysis spectrometers have been in use for the analysis of wear metals, contaminants and additives in lubricating oils for almost 50 years. They have become the mainstay and primary analytical tool of most machine condition monitoring programs based on oil analysis. Spectrometers have evolved from large instruments that take up the better part of a laboratory, to smaller table top instruments. Analysis times have decreased from hours to seconds, and the instruments no longer have to be operated by experts to obtain excellent analytical results.

Spectrometers using the rotating disk electrode (RDE) technique, long an established and accepted method, had become somewhat forgotten and ignored due to the commercialization of the more modern inductively coupled plasma (ICP) excitation technique. In the last five years, all this has changed. There has been what some consider to be a "rediscovery" of the RDE oil analysis technique due to a variety of innovations, inventions and expanded capabilities, all of which have lead to more

effective and productive used oil analysis programs in the military and commercial sectors.

Digital Technology Enhancements: Digital technology has had a major impact in the design and capabilities of oil analysis spectrometers. It has influenced the design and features of excitation sources, optical system size and capabilities, and readout and data management systems.

All excitation sources are based on simple electronic circuitry using discreet components. Development trends have been towards solid state excitation circuits which result in cost, size and serviceability improvements. One of the side benefits of applying solid state technology is the ability to eliminate transformers that are bulky and extremely heavy. Excitation sources for RDE spectrometers with solid state ignition circuitry have recently been introduced to the market. They improve instrument stability and greatly reduce operator periodic maintenance requirements. The need to adjust source frequency to compensate for voltage or environmental changes has also been virtually eliminated. This is one of the few areas where digital technology actually slightly increases the cost, but the advantages in performance and reliability are well worth it. Additional advances in solid state circuitry can be expected in the next few years.

The optical system of a spectrometer has always been the primary factor in determining the size of an instrument. Improvements in gratings have made it possible to reduce size without sacrificing performance or dispersion. The early instruments with 3 meter (9 feet) focal curves were replaced with 2 meter, then 1 meter and today as small as 0.3 meter optics. Reduction in focal curve size due to solid state detectors have made it possible to build much smaller instruments with better stability. Advancements in fiber optic technology have also led to further improvements in stability, flexibility and size of optical systems.

The optical system is still the most expensive, the largest and the most delicate component of an instrument. However, replacements for expensive photomultiplier tubes in the form of solid state charged coupled devices or CCD detectors has changed all this. This technology provides devices, by a variety of processes, consisting of many small light sensitive semiconductors (pixels) which may be arranged in a single row (linear array) or as a rectangle or square (area array). CCD technology is widely applied in such commonplace and reliable devices as video cameras, copy and fax machines. Consequently, a robust industry exists to supply and improve such devices and they are available at favorable prices, Fig. 1.

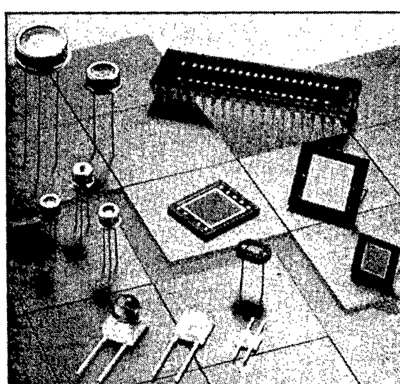

Figure 1, Examples of CCD Detectors

It is now possible to create smaller and more capable optical systems by placing CCD arrays along the focal surface of spectrometer optics, Fig. 2. This eliminates the need for expensive photomultiplier tubes and selection of elements prior to delivery of an instrument to a customer. CCD technology makes virtually any wavelength available for an analytical program and can be selected through the operating software. Resolution may not be improved in all cases, but accuracy can be improved since CCD arrays offer an unlimited possibility of selecting primary wavelengths and locations for background subtraction and referencing, with much greater freedom than current photomultiplier tube detector technology allows.

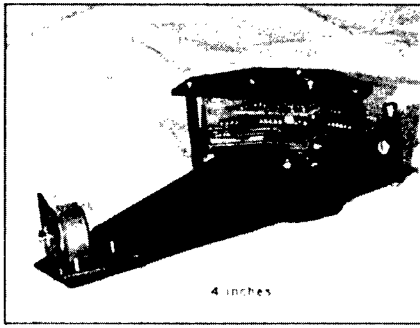

Figure 2, Optical System with CCD Detectors

CCD technology has already been incorporated in several commercial ICP spectrometers, but not demonstrably with the cost/benefit that it might ultimately derive. It is, however, an area where we can expect to see major developments in the next year or two.

Digital technology was applied in spectrometer readout systems with the introduction of the early mini-computers. Computerization made it possible to rapidly reduce vast amounts of data into figures and units readily understandable by the user. In the past, readout system hardware was complex and differed greatly among manufacturers. Today, except for one or two circuit boards, the personal computer is becoming more and more the only electronic readout system required for the spectrometer. It provides instrument control, data processing and troubleshooting.

Automation: Automation for the RDE spectrometer has always been difficult due to the need to replenish the graphite electrodes after each analysis. The rod electrode, in particular, has been a challenge to handle by robotics, since it not only must be sharpened after each burn, but also becomes shorter after each sharpening. A novel new robotics system has been developed which overcomes these hurdles.

The practical solution to RDE spectrometer automation is to use two graphite disc electrodes, Fig. 3. This eliminates the need to sharpen electrodes and greatly simplifies operation. The automation system consists of two parts, a robot to exchange the consumable disk electrodes and an automatic sample changer. The robot dispenses new graphite electrodes for each analysis and removes the used ones. The need to set the analytical gap size has also been eliminated since the disk electrode shafts form a fixed gap. An robotics arm in the sample changer automatically introduces each of 48 oil samples in succession, at a rate of 80 samples per hour, and without the need for sample dilution.

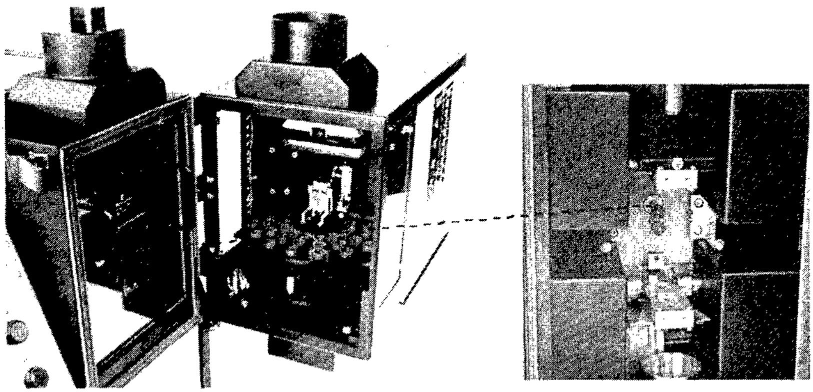

Figure 3, Robotics for RDE spectrometer

The entire automation system mounts to the spectrometer sample stand and fulfills all the functions of sequentially introducing and removing oil samples and exchanging graphite electrodes. It is self contained and works independently of the spectrometer operating software. Although operation is automatic, it also has the capability to manually sequence through each of the robotics functions. Automation also improves repeatability by eliminating operator variances and maintains JOAP correlation.

Large Particle Size Analysis Capability: The ability to detect and quantify large wear and contaminant particles has always been considered to be one of the shortcomings of spectrometers. Few will agree as to the actual detrimental impact on a condition monitoring program, but most will agree that the practical particle size limitation of spectrometers are at particles below 5 micrometers for ICP and AAS, and at particles below 10 micrometers for RDE [1, 2]. Today, the particle size limitation of RDE spectrometers has been eliminated with simple ancillary systems such as the rotrode filter spectroscopy (RFS) method.

Rotrode filter spectroscopy (RFS) makes use of the fact that the carbon disc electrodes used in rotating disc electrode (RDE) spectrometers are themselves porous. A fixture is used to clamp the discs so that oil can be drawn through the outer circumference of the discs when a vacuum is applied to the inside of the discs, Fig. 4. The particles in the oil are captured by the disc. The oil is then washed away with solvent, the disc is allowed to dry, and the particles are left on the disc electrode so that they are vaporized and detected when run on the RDE spectrometer. It is a technique whereby the normal analysis of the oil sample serves to provide data on particles that are dissolved to 10 micrometer in size, and the RFS technique analysis provides data on large particles [3]. A multi-station fixture is used so that a number of samples can be filtered at one time. Several commercial laboratories offer RFS to provide a more comprehensive analysis of used oil samples.

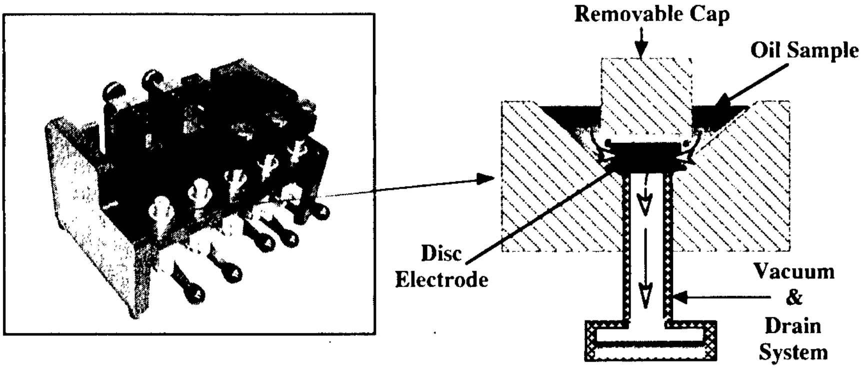

Figure 4, Rotrode Filter Spectroscopy (RFS) Fixture

Expanded Applications Capabilities: Although the RDE spectrometer is still designed primarily for used oil and fuel analysis, several methods and recent enhancements have increased productivity through expanded capabilities. They include the ability to analyze engine coolants, sulfur in oil and fuel, and oil degradation through changes in conductivity.

A used coolant analysis program determines both the coolant condition and the presence of any contaminants or debris. The coolant fluid can be used as a diagnostic medium as the coolant carries not only heat away from the engine parts but also carries fine debris from the interior surfaces of the cooling system. Analysis of the wear debris can provide important information about the condition of the internal parts of the cooling system.

Some machine condition monitoring programs have gone beyond used oil analysis and also provide data on the coolant system. The application of coolant analysis, however, has been limited due to additional cost and the time required to analyze samples. Until recently, ICP or AAS spectrometers have been used exclusively for this purpose. Although they provide good analytical data, the ICP is expensive and complicated to operate, and the AAS is slow since only one element is analyzed at a time. Today, several major commercial oil analysis laboratories have switched to the RDE technique for coolant analysis. This was made possible with minor hardware and software modification to the RDE spectrometer. It has been shown that the RDE technique correlates well with ICP and AAS techniques on new coolants and is more efficient on used coolants that contain particulates [4].

On-site sulfur analysis in lubricating oils and fuels has long been desired, but until recently, was impossible with RDE spectrometers. When a sample is sparked, the light emitted by sulfur is of such short wavelength that it does not reach the optics because it is absorbed by oxygen in air. ICP spectrometers with optics housed in a vacuum system had to be used for this purpose. This is no longer necessary as RDE spectrometers can be modified to include the capability to analyze sulfur. A compact, argon purged optic mounted near the sample stand of the spectrometer has been adopted for this purpose, Fig. 5. It is argon purged but consumption is minimal due to

the small size of the optic and the short optical path to the spark. It can be turned on and off as required to coincide with those samples that require sulfur analysis. With this enhancement, sulfur can be analyzed on the RDE spectrometer along with the remaining routine elements.

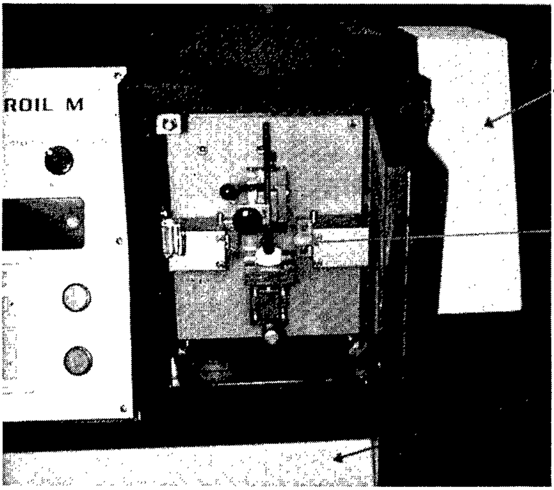

Figure 5, Sulfur Analysis Optical System Mounted on RDE Spectrometer

Finally, another RDE enhancement to analyze oil degradation along with routine wear metals is currently under test by the U.S. Air Force at Wright Laboratories. The technique is referred to as tandem conductivity technique (TCT). It measures used oil's conductivity, a sign of degradation and an indication of "burnt oil". A RDE spectrometer has been upgraded with TCT which includes a measurement circuit, sample table modification to adapt a special oil sample vessel, and software for calibration and readout of the conductivity measurement, Fig. 6.

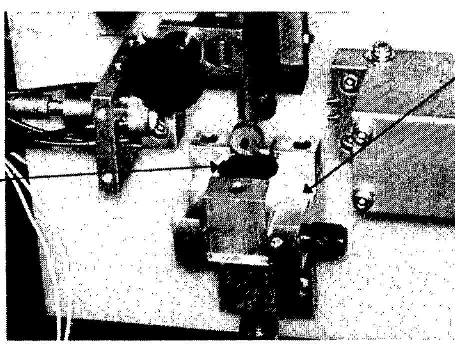

Figure 6, TCT Sample Stand

The RDE analysis with TCT is almost identical to current procedures and the conductivity measurement is made during the first four (4) seconds of analysis followed by the normal 30 seconds of wear metal analysis. Initial conductivity testing at the JOAP TSC in Pensacola, FL on actual "burnt oil' samples has been encouraging and has shown good correlation to other methods [5].

Conclusion: The rotating disc electrode (RDE) spectrometer has had a long and successful history as a workhorse instrument in the oil analysis laboratory. It has made a major comeback in recent years; just as new techniques such as ICP were thought to be an ideal replacement. Through the application of new technology, innovative inventions and common sense, the RDE spectrometer has re-established itself as the primary oil analysis spectrometer in military and commercial machine condition monitoring programs.

Spectrometers for oil analysis have evolved from instruments that had to be used in environmentally controlled laboratories and by expert and well trained scientific personnel. Today they have become easier to operate, smaller in size, mobile, and more robust for use in non-laboratory environments. They have become more efficient due to automation and expanded capabilities beyond routine oil analysis. The net effect has been an analytical capability that provides a great amount of information immediately and at the site where it is actually needed.

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Tandem Technique for Fluid Testing

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Abstract: A spectrometer's analytical sample stand is modified to incorporate a conductivity sensor to measure the electrical properties of liquids prior to spectrometric oil analysis (SOA). The sensor is positioned either in the bottom of the fluid sample container or in a probe dipped in the oil container. The sensor configuration is designed for high sensitivity by using coplanar electrodes of a highly conductive material such as copper with large surface area sheathed in a protective alloy material and mounted on a nonconductive substrate. The sensor electrodes are on the order of several hundred micrometers in width and positioned very closely so that the distances between them are on the order of their width. Any small changes in the conductance of the oil sample can easily be detected. The electrodes are connected to a circuit where the signal is integrated and printed a few seconds prior to initiation of SOA. Conductance measurements provide values proportional to the magnitude of oil degradation. A fresh oil of the same formulation as that of the used oil being measured may be used to establish a precise zero baseline and any deviation from this value is indicative of thermal and oxidative stressing of the oil.

Key Words: Condition monitoring, conductivity, electrical properties, lubricant degradation, thermal stressing.

Introduction: Fluid condition monitoring is a technique that involves the analysis of, e.g., a lubricant in field use for the purpose of assessing either its level of degradation or its residual capacity to perform some important tribological function. Changes in engine parameters or conditions which can affect the lubricant itself may or may not be coincident with changes in the level of wear debris in the lubricant. For example, a lubricant ages or degrades in normal operations, sometimes to unacceptable level without any abnormal operation, of the engine. Thus, monitoring can be used to assist in the determination of the proper interval for oil changes. The condition of the used oil is determined by detecting changes in certain chemical or physical properties of the oil caused by degradation of the oil basestock or depletion of the additive package. For properly running engines, the physical properties or chemical composition of the oil change at a certain rate, generally quite minimally, until the additive package is depleted. When abnormal operating conditions occur, e.g., an increase in aeration rate of the oil (excessive seal leakage, deteriorated "O" ring, cracked diffuser cases, etc.) and/or an

increase in oil temperature, the rate of oil degradation increases and the physical properties and chemical composition of the oil change commensurately. In these cases, lubricant monitoring can identify abnormally operating turbine engines which cannot be identified by the more frequently encountered monitoring of wear debris. In these situations, detections in lubricant condition supplement wear metal analysis in detection of atypical mechanical system operation.

Background: While a relationship exists between the degree of oxidation degradation and electrochemical properties of a lubricant, electrochemical measurement techniques of used oils is complicated by the effects of different additives and basestocks [1]. Orudzheva [2] reported that the electrical resistance, dielectric constant, and dielectric loss of base lubricating oils were similar but were changed by various additives. Keller and Saba [3] used a dielectric constant tester, which measures changes in the dielectric constant of a lubricant, to analyze gas turbine engine lubricants that had been stressed in laboratory oxidation tests. The data were evaluated with respect to total acid number and viscosity values of the lubricants and displayed meaningful correlation when evaporative loss of the lubricant was minimal.

Cyclic voltammetry is a technique which determines the concentration of specific compounds or groups of compounds by measuring the current generated from their electrochemical oxidation or reduction [4]. It is based on the quantitative measurement of the reduction wave generated from both the original and generated antioxidant species in the oil sample. A relationship was shown to exist between the logarithm of the wave height, which is proportional to the concentration of the various antioxidant species, and the remaining useful life of the lubricant.

The Complete Oil Breakdown Rate Analyzer (COBRA) [5,6,7] has been used as a lubricant monitoring technique for ester based turbine engine lubricants. Any changes in the COBRA readings of used lubricants will depend on the condition of the oil and on its formulation. By detecting the changes in the electrical properties of used oil samples with the COBRA, the United States Air Force was able to identify a total of 30 abnormally operating engines between May 1980 and August 1982 [6]. It has been reported that there is a relationship between the total acid number and COBRA readings and between the degree of degradation and COBRA readings [5,6,7]. Therefore, any changes in the COBRA readings of used lubricants are indicative of the condition of the oil and its formulations.

Many lubricant monitoring based on electrical, electrochemical, chemical, thermal and spectrometric analytical techniques have been developed for hydrocarbon or ester based fluids [1]. Among the techniques investigated in the literature, the electrical property is one of the simplest techniques to adapt in the development of a tandem analysis for the condition of oil and wear metals. Minimal modification of the spectrometer is needed in addition to the initial cost of the sensor and its installation. Verification of the usefulness

of conductivity in monitoring oil degradation [5,6] justified its development into this tandem technique.

Description of Apparatus: The analytical device unit is designed to permit electrical conductivity measurements of a fluid in a spectrometer just prior to the spectrometric analysis. Measurements are performed using a probe inside the test sample container before the sample burn for spectrometric wear metal analysis. Figure 1 shows the sample stand of the spectrometer with the conductivity sensor being in the bottom of the oil vessel in one configuration. The contact of the sensor with the connector pins is made when the vessel is placed onto its holder. When the vessel stand is raised into position, a proximity switch initiates the test sequence. If the door to the spectrometer compartment is closed prior to the completion of the conductivity measurement, the electrodes are disconnected and a zero reading is recorded. The electrode disconnect is controlled by a separate relay board which is connected to the spectrometer interlock system. When the test is initiated, a voltage square wave on the order of $\pm$ 2.5 V is applied to the electrode. The applied frequency is about one hertz in order to minimize capacitance effects. Current, on the order of less than one microampere, through the oil is detected, rectified and filtered. Since the current tends to be small, a gain of approximately ten million is used. A delay of five seconds is needed to stabilize the reading. After this delay, a total of several hundred data points are made and averaged.

The data are processed by a built-in microprocessor. Once the processor has averaged the readings it converts the data to an RS-232 format and sends the results to the printer. The fluid assessment takes less than six seconds. Control of the printer is returned to the spectrometer and the wear metal test proceeds.

Figure 2 is a photograph of the oil vessel in the sample stand while Figure 3 shows another configuration of the conductivity sensor where the sensor is a probe dipped in the oil. The former configuration is preferred because the oil shields the sensor from the dynamic sparking activity of the discharge during the atomic emission wear metal analyses. The sensor is a long planar electrode of arbitrary geometry. Its sensitivity is dependent on the surface area which in turn is proportional to the length and width of the electrode. Increasing sensor area increases sensitivity of the sensor.

Discussion of the Results: The conductivity sensor is applicable to fluids typically analyzed by the atomic emission spectrometer. Aviation lubricants, internal combustion engine oils, and hydraulic fluids are among the fluids commercially analyzed. Since different classes of oils generate different values of conductivity, the same class of fluid must be referenced when analyzed to get good correlation of data. A fresh lubricant, similar to the oil tested is ideally used as the reference point.

A T-63 turbine engine stand test was conducted to evaluate a 4-cSt ester base lubricating oil. The lubricant was sampled periodically to determine its physical properties as a function of engine test hours. Wear metals, total acid numbers, viscosities, COBRA,

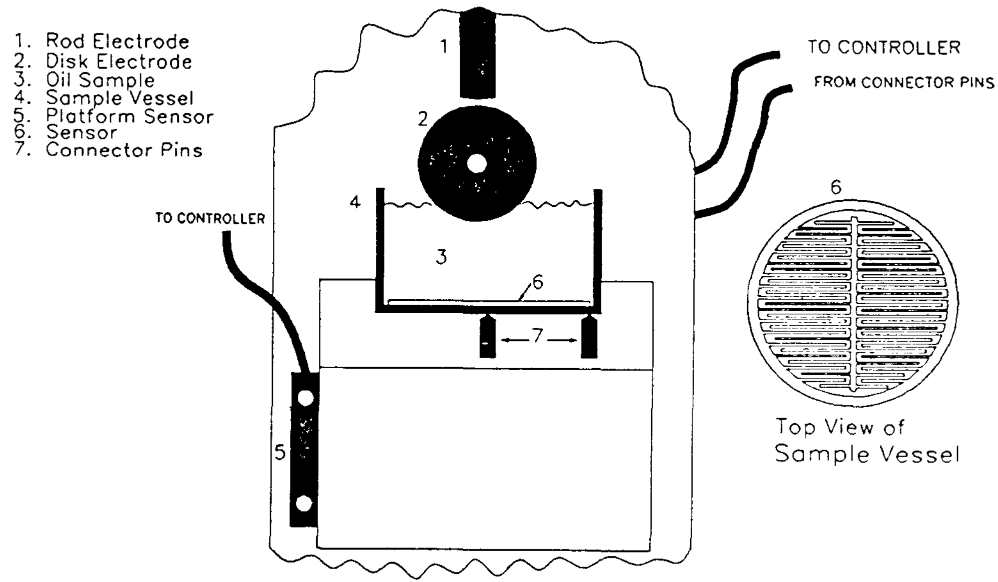

Figure 1. Schematic of Coplanar Conductivity Cap Sensor and Analytical Sample Stand

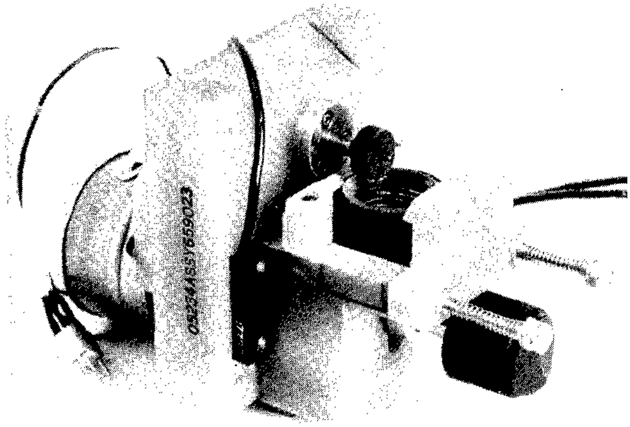

Figure 2. Cap Coductivity Sensor

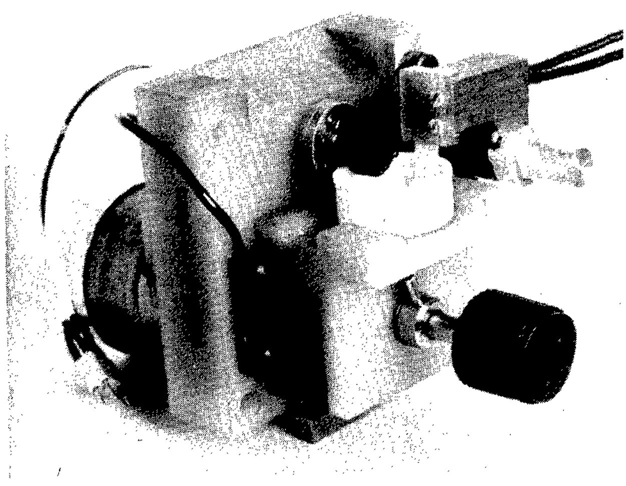

Figure 3. Conductivity Probe

percent lubricant life remaining and conductivity were measured and compared (Table 1) For comparison, the above readings are plotted versus the first 65 hours of the test [Fig 4]. There was no appreciable increases in wear metals indicating no problems with oil wetted components. Also, the changes in viscosities and TAN values were not significant indicating no appreciable oxidative degradation of the lubricant. However, the basestock degradation seen from the percent basestock remaining study, as shown in the section below, occurs as a result of the thermal stressing of the lubricant and seem to contribute to the significant increases in COBRA and conductivity values. A good correlation is shown below COBRA values of 80 for the first 40 hours of engine testing (Fig. 4). Beyond this testing time the conductivity cup values accelerate at a faster rate than the COBRA. The conductivity data were also correlated with percent basestock of the lubricant remaining, i.e. the lubricant that is not consumed by the high temperature stressing. The results showed a definite correlation in spite of oil make-up during the course of engine test. After the engine test, it was confirmed that the high conductivity and COBRA values were the results of one of the bearings experiencing abnormally high temperature.

A collection of "black oil" samples from gas turbine engines that had been analyzed by COBRA were analyzed for conductivity using the subject device. A "black oil" is an oil that has experienced high temperature beyond its capability in a gas turbine engine and becomes visibly darkened or "black" due to the build-up of carbonaceous material as a result of thermal-oxidative stressing. Conductivity and COBRA values plotted in Figure 5 show a high degree of correlation between the two techniques indicating that conductivity can reliably measure thermal-oxidative stressing of the lubricant in authentic used oil samples.

Oil sample collected from commercial turbine engines were also analyzed by COBRA and conductivity. In spite of the scatter in the results shown in Fig. 6, one can still observe some degree of correlation between the two techniques.

Conductivity of aircraft mineral based hydraulic fluid and aircraft or automotive mineral based lubricating oil was measured as a function of stressing time. The data were also compared with the COBRA. During the 24-hour testing period, the fluids were periodically sampled to measure the changes in electrochemical properties. For the hydraulic fluid, there was a slow increase in conductivity which accelerated after the 8-hour test period. However, COBRA values did not significantly increase until the 16th hour of testing. This is a good indication of how sensitive and predictable this technique is. For the mineral oil, there was a dramatic decline in conductivity after the first two hours of testing followed by a period of no change and then a significant decline after the 16th hour of testing. COBRA values agreed by showing a dramatic decrease. The data establish the capability of the subject device to correlate with COBRA readings and, therefore, determine the condition of a fluid.

TABLE 1

GAS TURBINE ENGINE STAND TEST USING FULLY FORMULATED ESTER BASE LUBRICANT

Test Time h	**Visc.,cSt** 40°C	**TAN** mg KOH/g	**COBRA***	**Conductance**	**Dielectric**
0	17.69	0	6	29	0
8	18.03	0	41	168	0
16	17.98	0	45	228	0
24	17.99	0	55	287	0.6
32	18.13	0.05	66	331	0.6
40	18.25	0.04	66	380	0.6
48	18.16	0.11	76	429	0.8
56	18.29	0.10	90	473	0.8
64	18.44	0.09	90	532	0.9
72	18.40	0.08	87	566	1.0
80	18.54	0.08	90	602	1.0
88	18.48	0.10	88	629	0.9
96	18.43	0.09	94	649	1.1
104	18.52	0.12	96	677	1.2
112	18.50	0.12	100	693	1.3
120	18.59	0.14	104	718	1.1
128	18.69	0.17	110	768	1.2
136	18.61	0.20	107	789	1.2
144	18.64	0.20	116	796	1.3
151.3	18.67	0.23	122	803	1.4
159.3	18.71	0.20	115	842	1.4
168	18.75	0.21	126	844	1.5
174.7	18.86	0.22	126	870	1.5

*COBRA= complete oil breakdown analyzer

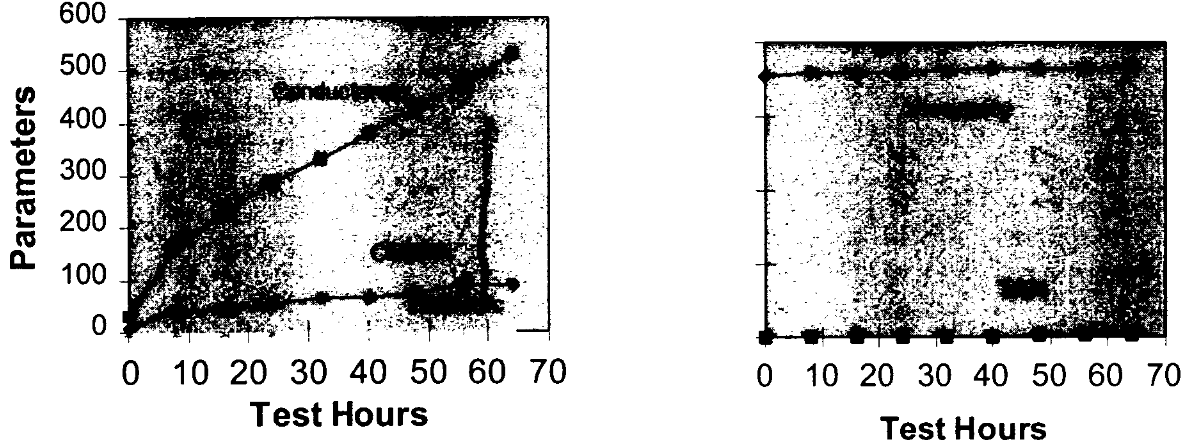

Figure 4. Gas Turbine Engine Stand Test for 4-cSt Fully Formulated Ester Base Lubricant

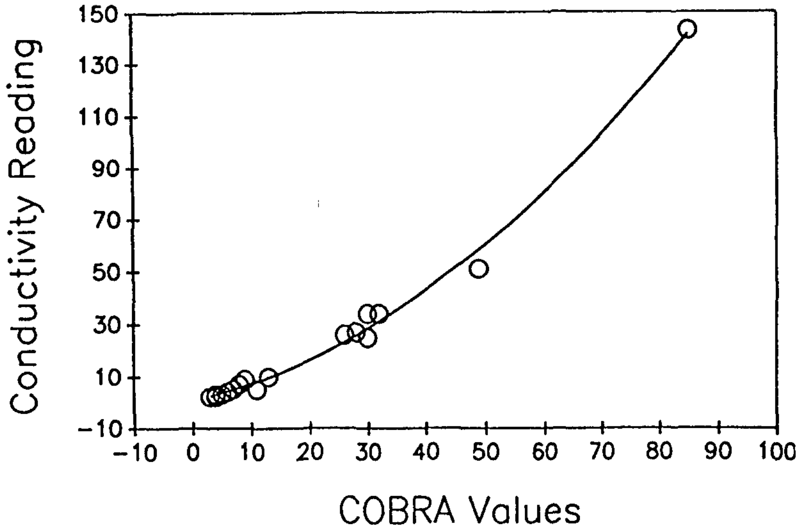

Figure 5. Conductivity Relationship to COBRA Values for Used Gas Turbine Engine MIL-L—7808 Lubricants

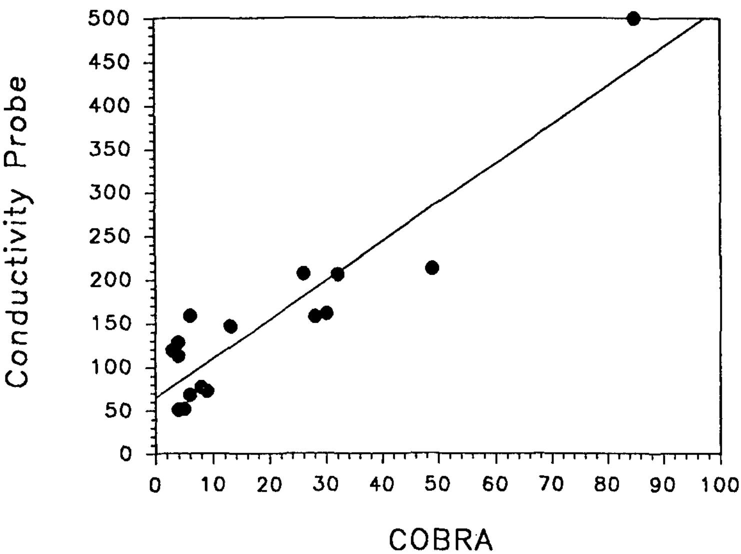

Figure 6. Conductivity Relationship to COBRA Values for Used Commercial Gas Turbine Oils

Based on established practices where COBRA has been used to determine the condition of turbine engine ester lubricants [5,6,7], the correlation of COBRA and conductivity of lubricant samples establishes the merit of the subject spectrometric device in measuring lubricant condition.

In conclusion, the tandem technique measures the electrical property of the fluid and wear metals. These measurements are made sequentially and with minimum sample handling or modification. Traditionally, these type of measurements are made on two separate pieces of equipment which is costly and time consuming. The all-in-one technique gives a fast turn around results with no additional consumable items. Its applicability has been demonstrated and correlated with other existing techniques.

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Novel Sensors for Portable Oil Analyzers

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Abstract: We present progress of research and design in the area of liquid sensors for condition-based maintenance where accurate portable devices for monitoring hydraulic and lubricating fluids are desired. Issues addressed include dielectric modeling, capacitive calculations, a novel 'electrogravity' mechanism, and MEMS (microelectromechanical systems) applications. Measurements of capacitance, of frequency response, of oxidation effects, and of breakdown voltages, all as a function of contaminant concentration, have been carried out.

Key Words: Condition monitoring; lubricant contamination; portable instruments; impedance spectroscopy; numerical computation.

Introduction: We have worked intensively over the past few years to produce portable sensors capable of detecting contaminants at increasingly improved resolution [1]. A portable instrument can provide an indication as to the lubrication condition of an oil without the need for any sample preparation such as a separate measurement or use of any chemicals.

Section I - Present Commercial Instrument and Outline of Paper: The latest PREDICT portable instrument, Navigator v1.0, is based on impedance spectroscopy. It measures the magnitude of the impedance of the system represented by the sensor electrode and the oil sample, at different frequencies. Changes in the permittivity and conductivity of an oil can be observed and differentiated. Four distinct frequencies lying in the .1-120 kHz range, have been chosen as a result of extensive empirical research with known oil samples. The frequencies are as follows: Two low frequency readings (100-500 Hz) are used to find changes, on a logarithmic scale, in the conductivity of the oil. The presence of water dominates these frequencies. One intermediate frequency reading (10 kHz) is still sensitive to conductivity, but now in

an approximately linear fashion. One high frequency (120 kHz) reading is taken to measure changes in the permittivity of the oil. The effects of wear debris increase at the higher frequencies.

The instrument reads data for each frequency and stores it in memory. A baseline is established by running a clean sample. A comparison is then made with the data obtained for a (possibly) contaminated sample, and, if changes are greater than an acceptable tolerance, at any frequency, the sample is rejected ('out of limits') and sent to a laboratory for further analysis. The Navigator v1.0 tolerances have been set empirically such that the calls made by the instrument match independent and calibrated tests at the 80% level. The instrument is designed to give an answer within two minutes.

Contaminants such as oxidation, wear particles, water or any contaminant that has a different dielectric constant than the oil being measured will affect a permittivity measurement. Contaminants such as water, soot, very large (175 μm, say) wear particles, along with depletion of the additive packages in some types of oil, can affect the conductivity of the oil. In some cases, the apparent effect can be much larger than the classical electrostatic calculation, due to electrochemical effects (clouds of counterions surrounding the contaminant particle).

In the present paper, we describe certain experiments and modeling that have been carried out in conjunction with the development of Navigator v1.0 and the next generation of such detectors. At any AC frequency, conductive and capacitive effects can be described together via evaluation of the complex dielectric constant. In the second section, we analyze a simple capacitance measurement in terms of the classical Maxwell-Wagner theory for the dielectric constant at low concentrations. In the third section, modeling is carried out for the electric fields of the electrode configurations used in the sensors. Experiments and the modeling for the frequency spectrum of the sensor capacitance are described in the fourth section. Oxidized oil can also be detected by measuring the phase angle associated with an effective sensor impedance of the sensor. Directions using MEMS technology are also indicated in that section. The combination of the important effects of gravitational settling and local electric fields is delineated along with a wear particle discussion in the fifth section. Concluding remarks comprise the last section.

Section II - Modeling Heterogeneous Dielectric Material: A simple analysis of a colloidal mixture of spherical particles interacting with the suspending medium, is the so-called Maxwell-Wagner (MW) model [2, 3, 4, 5]. The analysis assumes that a small fraction q of an 'impurity phase' with conductivity (σ_p) and dielectric constant (ϵ_p) is dispersed in a fluid with conductivity (σ_m) and dielectric constant (ϵ_m). Under the assumption of a constant electric field, the effective dielectric constant is found in the references to be given by

$$\frac{\epsilon^* - \epsilon_m^*}{\epsilon^* + 2\epsilon_m^*} = q\frac{\epsilon_p^* - \epsilon_m^*}{\epsilon_p^* + 2\epsilon_m^*}$$

with

$$\epsilon^* = \epsilon - j\sigma/\omega \tag{2}$$

and angular frequency ω. We can test this formula against experiments involving simple parallel-plate capacitors. The experimental data corresponding to 'Exp. 1' and a theoretical calculation based on the MW model are compared in Table I. The parallel-plate experiments were performed using an HP 16452A liquid test fixture with an accuracy better than the two digits quoted after the decimal point. In the Maxwell-Wagner calculation, the relative dielectric constant of oil is taken to be 2.2, the relative dielectric constant of water to be 81, and the conductivity of water to be 10^{-4} S/m. While the trends are in the right direction in the comparison found in Table I, the quantitative discrepancies suggest additional factors should be taken into account. The data for 'Exp. 2' will be discussed in section IV.

Table I
Capacitance Values of Contaminant Detectors

Frequency	Concentration	Exp. 1 [a]	MW [b]	Exp. 2	Layers
N/A	0	22.69 pf [g]	N/A	40 pf [c,g]	40.2 pf [c,g]
N/A	0	10.59 pf [h]	N/A	18 pf [f,h]	15.0 pf [f,h]
10 Hz	1000 ppm	22.70 pf	22.76 pf	40.4 pf [c]	N/A
10 Hz	5000 ppm	24.05 pf	23.03 pf	2.54 μf [d,e,f]	6.5 μf [d,f]
100 kHz	1000 ppm	22.69 pf	22.75 pf	40.1 pf [c]	52.0 pf [c]
100 kHz	5000 ppm	22.88 pf	23.01 pf	55 pf [e,f,i]	245 pf [f]

[a] displays the experimental results for a parallel-plate capacitor.
[b] displays the results for the Maxwell-Wagner calculation pertaining to the parallel-plate capacitor Experiment 1.
[c] A prototype I sensor was used with substrate dielectric constant of 10.4.
[d] This value was at 20 Hz.
[e] The time-dependence due to water settling must be considered. The present measurement was taken after 1 hour of settling time dependent.
[f] A prototype II sensor was used with substrate dielectric constant of 4.2.
[g] The values correspond to pure oil.
[h] The values correspond to air.
[i] This value was measured at 1 MHz.

Section III - Capacitance of Dielectric Layers and Coplanar Electrodes: The PREDICT sensor described above has a coplanar geometry where electrode tracings are laid out over single planar surfaces. An increased contaminant presence leads specifically to an increase in the capacitance of the electrode array as it is immersed in the oil.

The coplanar array of interleaved conducting strips is supported by a fiberglass substrate. The rectangular coplanar electrode has approximate dimensions of 5 cm by 5 cm and a thin layer of test oil (with a depth of about 5 mm) is sampled by pouring the oil over the electrode. The observed changes of capacitance (ranging from picofarad to microfarad values) upon introduction of 1000-5000 ppm of water are in

adequate agreement with theoretical modeling. The latter is described next, followed by an experimental discussion. The results of the this work have been used in the development leading to the design of Navigator v1.0.

A two-dimensional Green function method, such as that used in parallel arrays of microstrips, can be employed to obtain a capacitance per unit length, and this leads to an accurate estimate of the total capacitance for those systems having gap distances between strips much smaller than the overall array dimensions and where the contaminant effects are not yet considered. Following the equations in [6, 7], the electrostatic potential V is

$$V(\vec{r}) = \int_{\Omega} G(\vec{r}, \vec{r'})\rho(\vec{r'})d^3\vec{r'} \tag{3}$$

where G is the Green function, ρ is the electric charge density, and Ω denotes the conductor surface over which the charge is distributed. The charge distribution on the given coplanar tracing geometry is found by considering Eq. 3 as an inverse problem [8, 9]. The Green function satisfies a Poisson differential equation:

$$\vec{\nabla}(\epsilon\vec{\nabla}G(\vec{r}, \vec{r'})) = -\delta^3(\vec{r} - \vec{r'}) \tag{4}$$

It is assumed that there are several layers above and below the copper coplanar traces building up in the y direction, and the traces may be considered to be infinite along the z direction. Within each layer where the dielectric constant is in fact constant, Eq. 4 reduces to Laplace's equation. In terms of a spectral domain (Fourier transformation of the Green function in the x variable), the solutions to Laplace's equation are the well-known exponential functions in y. The lengthy details of the full solution obtained after the boundary conditions between layers are applied are to be published elsewhere.

A simple analytical form for the Green function in the spectral domain of a special case can be found. If we have only two thick layers with dielectric constants ϵ_1 and ϵ_2 above and below the traces (that is, the heights of two layers are considered to be large compared to the dimensions of the traces), the capacitance of the coplanar electrodes is

$$C = \frac{\epsilon_1 + \epsilon_2}{2\epsilon_0}C_0 \tag{5}$$

where C_0 is the capacitance in free space (itself computed with a Green function method). The computer codes written for a general set of layers can be verified against simple results such as Eq. 5.

Consider two cases with no contaminants for 'Exp. 2' in the top two rows of Table I. One corresponds to a thick oil layer on top of a prototype electrode and the other to the case where the electrode is simply exposed to air, both with finite thickness for their substrates taken into account. The theoretical results agree well with the measurements. The capacitive measurements were again carried out with an HP network analyzer. The slightly higher value for the measurement in air is likely due to humidity.

The response curve in Fig. 1 indicates the thresholds or detection limits of the Navigator v1.0 instrument for water contamination.

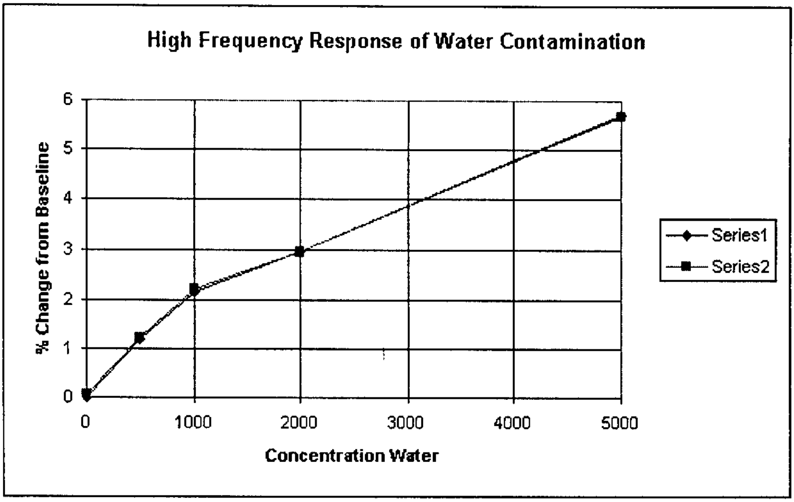

Figure 1: Water response curve of the Navigator v1.0 for 120 kHz. The water concentration is in ppm of oil.

It is observed from the figure that a 0.5% threshold on the high frequency measurement gives an 'out of limits' reading when there has been approximately 250 ppm or more change in the water concentration as compared to a reference oil. The water concentrations in the calibration curve of Fig. 1 are determined with a Water-by-Karl-Fischer titrator (D4928).

Section IV - Frequency Spectrum: We consider now the frequency dependence due to the presence of conductivity in the generalized dielectric constant. At the high frequency end, the conductivity effect is negligible. For lower frequencies, and if there is a nonvanishing conductivity in the layers, then Eq. 2 may be used to generalize the dielectric constants appearing in Eq. 5.

Table II
Capacitances for a water layer

Frequency	C_{exp}	$\lvert C_{theo}\rvert$
20 Hz	12.3 ± 0.1 μf	12.3 μf [a]
100 Hz	2.5 ± 0.5 μf	2.46 μf
1 kHz	270 ± 30 nf	246 nf
10 kHz	35 ± 15 nf	24.6 nf
100 kHz	3.4 ± 0.5 nf	2.48 nf
1 MHz	339 ± 19 pf	388 pf

[a] This is fixed by the experimental result.

One example is presented in Table II, where the oil layer is replaced entirely by water. The conductivity in water can be found by fitting the theoretical prediction to the

measurement at 20 Hz, obtaining the value of 3.9×10^{-3} S/m. The capacitances for other frequencies can then be computed. It is seen in Table II that the experimental results and theoretical estimations are in satisfactory agreement.

The next modeling is for two different coplanar traces with 1000 ppm and 5000 ppm water-contaminated oil samples. Columns 'Exp. 2' and 'Layers' in Table I represent the measured and computed results, respectively. The theoretical predictions are based on an assumption that the water has settled into a layer below the oil and on top of the electrodes. Because complete water settling takes a long time, the experimental measurements are smaller than the the computed results. However, there is better than order-of-magnitude agreement and this is impressive when it is recognized that the capacitance changes by six orders of magnitude over a similar change in the frequency range.

It is easy to see the capacitive dependence on frequency ω from an equivalent circuit model for the electrode-sample system, consisting of an effective resistor in parallel with an effective capacitor. When a sample is placed on the sensor, it changes the capacitance C and conductivity. The reactance of the capacitor is $1/(j\omega C)$. Therefore one can see that at a low frequency the reactance is very large and most of the current will flow through the resistor, thus revealing information about the conductivity. When the frequency is higher, the reactance of the capacitor is much less and most of the current will flow through the capacitor, revealing information about the permittivity. Thus one can see how the contributions from conductivity and permittivity can be separated to some degree by changing the frequency.

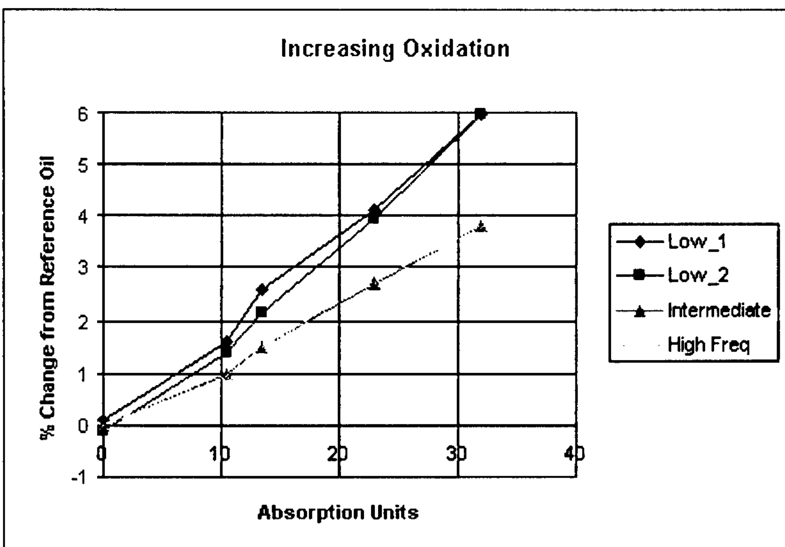

Figure 2: Oxidation Response Curves for Navigator v1.0

Oxidation of oil is an additional industrial problem. The current Navigator v1.0 can be used to detect oxidation levels as well. The response curves in Fig. 2 indicate the thresholds or detection limits of the Navigator v1.0 instrument for oxidation. The tolerance of frequencies are set such that the unit triggers an 'out of limits' reading for a change in 10 AU (absorption units) or more in oxidation. Oxidation is defined in the 1710 cm^{-1} region using a Fourier transform infrared (FTIR) spectrometer which indicates the presence of carboxylic acids in the lubricant.

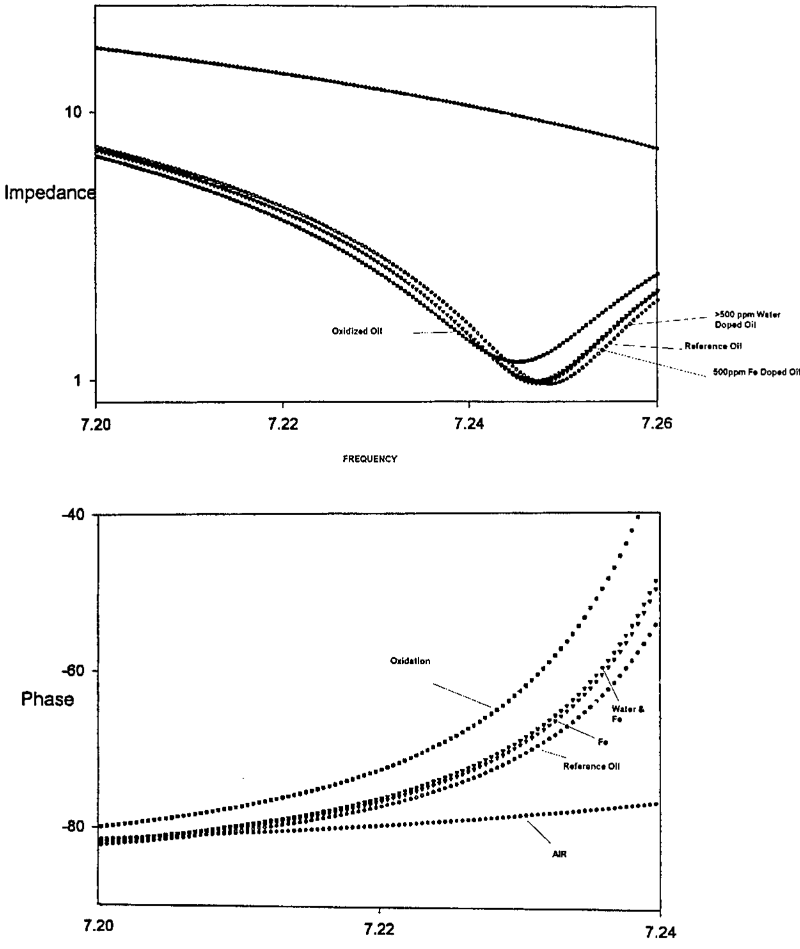

Figure 3: Impedance magnitude and phase as functions of frequency (log scale).

Other methods exist for measuring oxidation. Initial testing indicates that by measuring the phase angle and/or magnitude of the impedance near the resonance of the

grid, oxidation levels can be detected. Changes in an oil molecule caused by increased oxidation suppress the response of the orientation polarization of the molecule to a rapidly changing electric field. At lower frequencies this is not a problem, but at higher frequencies it adds to the loss and thus a reduction in Q and a change in phase. See the phase curves in Fig. 3 near the resonant frequency of the current sensor (20 MHz for an unloaded sensor).

In general, contaminants in the oil change the Q factor of the sensor. For example, doping an oil sample with ferrous wear particles lowers the resonant frequency, but does not appear to affect the bandwidth of the signal. However, oxidized oil both shifts the resonant frequency and increases the bandwidth. Again see Fig. 3 for the impedance magnitude curves.

There is an increasing interest in miniaturization of contaminant sensors for in situ monitoring. The sensor used for impedance spectroscopy with the present commercial instrument has been prototyped using MEMS fabrication techniques at the Case Western Reserve University MEMS laboratory through Ohio MEMSNet. The early prototypes have reduced the large (25 cm^2) scale sensor in the commercial Navigator v1.0 product to 1 mm^2. The impedance spectroscopy sensor fabricated on silicon is termed the MOS device for Miniature Oil Sensor and its applications are patent pending. The prototype devices have been wirebonded and packaged in a variety of housing for tests in real time and in situ applications. Dies have been fabricated specifically for water and oxidation, and a series of dies fabricated specifically for ferrous particle detection.

Section V - Electrogravity and Critical Voltages: Let us turn our attention to wear particle detection. The response curves in Fig. 4 indicate the thresholds or detection limits of the Navigator v1.0 instrument for 60 μm iron-particle concentrations. The thresholds on the corresponding frequencies are set such that the instrument reports an 'out of limits' reading when there is a 400 ppm or more change in Fe from the reference. A single 175 μm particle or a build up of particles amounting to 175 μm across the traces will also trigger 'out of limits.'

More sensitivity in the detection of ferrous particles is desired. To improve matters, we have discovered a technique separate from the capacitive methodology. If we immerse tracer electrodes, such as those used in capacitive sensing, in a wear-particle contaminated oil sample, we will observe current surges (from μA to mA in a typical case) through the electrodes as critical voltages are applied. What happens is that 60 micron particles, say, settle fairly quickly under the combined effects of gravity and the local electrode electric field. The particles tend to form bridges between electrodes, a phenomenon we refer to as 'electrogravity.' Some preliminary experiments have been carried out at this stage. The correlation with particle contamination down to the levels of 100 ppm is very encouraging. The breakdown voltages are in the range of 100-500 V.

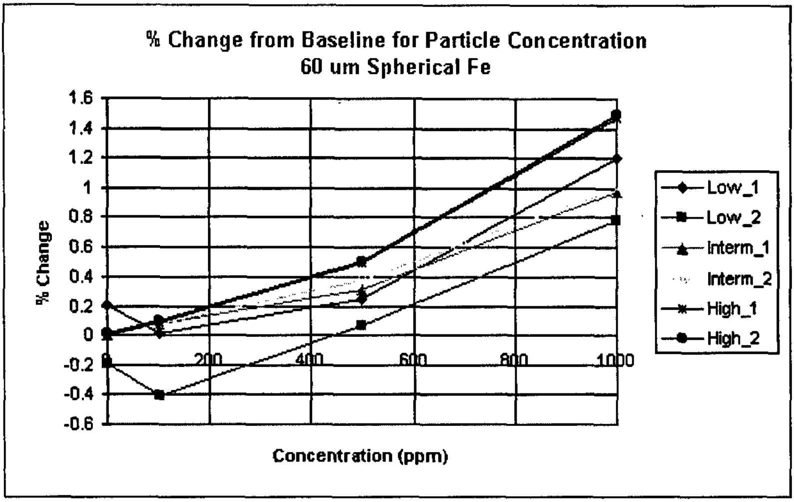

Figure 4: Ferrous Particle Response in Navigator v1.0

Section VI - Conclusions and Outlook: In predictive maintenance, changes in contaminant levels on the order of 100 ppm are of increasing significance. Toward this end, we have achieved a magnitude of order increase in the gain of the sensor from that of other sensors on the market by maximizing the capacitance per unit area of the sensor.

Reading the oil at four frequencies enables the instrument to separate changes in the conductivity and permittivity caused by contaminants. Also different types of oil have different characteristic spectrum, and with a little experience a user can differentiate between them. This is an obvious area for periodic software enhancements.

While the MW theory showed capacitive changes in the right direction for the contaminant modeling, we have found interesting deviations from this behavior. Equation 1 does not take into account synergistic effects between the contaminant and the base dielectric (oil), such as 'conduction hopping' of current carriers from one conducting contaminant particle to another, or, at higher electric fields, the lowering of the breakdown strength by contaminant particles. It does not account for the effect of contaminants which go into a true solution in the base oil (such as anti-oxidants). It may be useful to study these rather sensitive physical/chemical properties for a wide variety of lubricating oils, and establish proper operating regimes for 'combined sensors' which utilize information from dielectric constant, dielectric strength, and conductivity measurements. Additionally, it is useful to study purely mechanical effects (the settling of suspensions) to augment the electrical measurements and provide additional information.

Even at low operating voltages, apparent electrophoretic separation of the oil and

water is occasionally seen when a sample is left under applied fields for times of more than a few minutes. Thus we have already seen signs of gross electrical flow effects on fluid contaminants which we expect to become much stronger at higher electric fields. A suggestion in this paper is the intentional use of these electrophoretic or dielectrophoretic effects, rather than the disregarding of them as a nuisance.

Future MEMS work includes a next prototype run on SiC allowing for higher operating temperatures. The need for very high in situ operating temperatures for some systems is driving us to investigate MEMS photolithography with refractory metals. Incorporation of the voltage breakdown work is planned for applications in silicon. Packaging of this sensor in an existing engine plug is also being investigated.

Goals in the breakdown work are to reduce the high critical voltages required, and to reduce the waiting time under the gravity effect. The modeling of the phenomenon involves the calculation of the electric field and the application of Poisson statistics to find the optimum depth of oil layers in the sensor container. Our experimental results agree with preliminary estimates from Poisson statistical analysis. The present aim is to detect 100 ppm of 10-micron particles in oil. A principal emphasis for the future is the advancement of wear-particle sensors.

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IN-LINE OIL DEBRIS MONITOR (ODM) FOR HELICOPTER GEARBOX CONDITION ASSESSMENT

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Abstract: The development of an in-line, full flow oil debris sensor system for the engine nose gearbox of a military helicopter is described. The sensor is designed as a direct one-for-one replacement of an existing magnetic chip detector, located in the scavenge oil line of the gearbox. The sensor is based on an inductive measurement technique which enables the system to detect, count and classify wear metal particles by size and type (ferromagnetic or non-ferromagnetic) with a detection efficiency of close to 100% above the minimum particle size threshold of approximately 175 microns. The design requirements, principle of operation, mechanical design features and electronic design features of the sensor are discussed. The performance /characteristics of the sensor system, as measured during development testing, are also presented.

Introduction: The mechanical components of a helicopter gearbox operate under severe conditions of load, speed and temperature. Under these conditions, component damage can progress very rapidly from the point of an initial flaw to component failure, sometimes in a matter of only a few hours of operation.

Continuous monitoring is therefore required to detect the onset of failure and provide for safe shutdown of the gearbox. Magnetic chip detectors placed in the return oil flow from the gearbox traditionally have been used for this purpose. These devices, rely on the oil-borne wear debris particles to make contact with the sensing element and remain trapped by its magnetic field. In conventional usage, the detection efficiency of a chip detector is quite poor. Moreover, chip detectors are incapable of detecting non-ferrous wear metal particles and are prone to false alarms due to the build up of fine ferrous debris. In recent years, the manufacturers of chip detection systems have introduced "fuzz-busting" electronic circuitry to address this latter deficiency; but the effectiveness of these systems is still considered to be poor by most operators.

The Oil Debris Monitor (ODM), developed jointly by BFGoodrich Aerospace and GasTOPS, overcomes the limitations of conventional chip detection systems using an advanced, full-flow, inductive sensing technology capable of continuously monitoring wear metal particles (both ferromagnetic and non-ferromagnetic) in pressurized oil lines with a detection efficiency of 100%.

In 1996, BFGoodrich and GasTOPS undertook the development of an ODM system for McDonnell Douglas Helicopter Systems in response to McDonnell Douglas' requirement for a more effective oil debris monitoring capability for the engine nose gearbox of the AH-64 helicopter. A pre-production version of this system was provided to McDonnell Douglas for performance verification testing on a ground-based gearbox test rig. An in-service evaluation of the system on an operational AH-64 is presently in progress.

This paper summarizes the design requirements of the AH-64 ODM system. The principles of operation of the ODM are described and a brief description of the mechanical and electronic design features of the AH-64 ODM are provided. Sensor performance data obtained from controlled failure progression tests are presented. The results of system performance verification tests conducted by McDonnell Douglas are also presented.

System Design Requirements: The existing chip detector is installed in a port at the front end of the nose gearbox housing, near the bottom of the oil sump (Figure 1). The detector inserts into the flow path at the point where the oil pump draws oil from the sump. The oil is drawn over the sensing head of the chip detector at a rate of roughly 3 gpm, through a coarse mesh screen (which captures larger chips) and into an oil pump inlet cavity, cast within the outer wall of the gearbox housing.

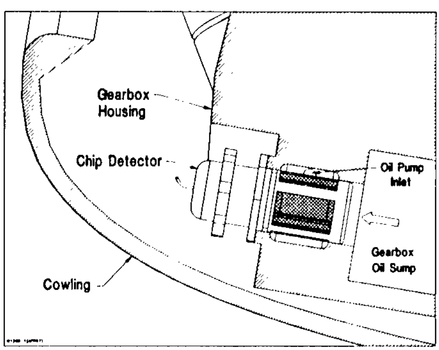

Figure 1 - Existing Chip Detector Installation

The basic design requirement of the ODM system is to replace, on a one-for-one basis, the existing chip detector. Hence, the ODM sensor is designed to be installed in the chip

detector port, without modification of the gearbox housing. Additional sensor design requirements include:

- operation with oil temperatures up to 285°F
- operation with vibration levels up to 6 g's from 15 to 2000 hz
- ambient air temperature up to 140°F
- no interference with the aircraft cowling which surrounds the nose gearbox
- minimum weight increase

The electronic control unit for the sensor is located remotely in an equipment bay with cabling run from that point to each of the sensor locations (left and right hand gearboxes). As well, the control unit supports a cockpit indicator to indicate warning and alarm conditions assessed based upon the amount of debris counted by the sensors.

System Operation: The ODM is through flow device which installs in the gearbox oil supply line and allows the entire oil flow to pass without obstruction. The sensor incorporates a magnetic coil assembly which is capable of detecting and categorizing wear metal particles by size and type (ferromagnetic and conducting non-ferromagnetic). The minimum detectable particle sizes are determined primarily by the inner diameter of the coil assembly and the operating environment (temperature, vibration, EMI etc.) of the sensor. For the AH-64 application, these minimum sizes are approximately 175 microns for ferrous particles and 350 microns for non-ferrous particles.

The magnetic coil assembly consists of three coils which surround a magnetically inert section of tubing. The two outside field coils are driven by a high frequency alternating current source such that their respective fields are nominally opposed or cancel each other at a point inside the tube and just under the center sense coil. Disturbance of the magnetic fields caused by the passage of a particle results in a characteristic sense coil voltage as shown in Figure 2. The amplitude and phase of the output signature is used to identify the size and type of particle. The amplitude of the signal is proportional to the mass of the particle for ferromagnetic materials and to the surface area of the particle for non-ferromagnetic materials. The phase of the signal for non-ferromagnetic particles is opposite to that of ferromagnetic particles, allowing a distinction to be made between the two types of wear metal materials.

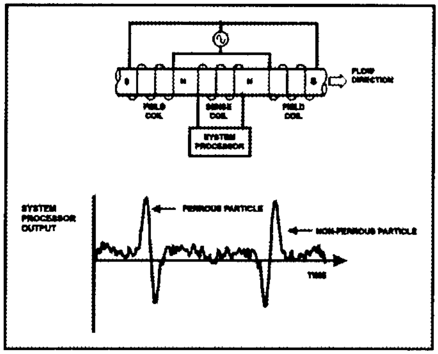

Figure 2: ODM System Operation

Odm Sensor Design: The ODM sensor design is based upon the use of an aluminum cast housing that incorporates the flow path for the oil, the support for the sensor coils and a housing for the on-sensor electronics. The design of this casting requires careful consideration to include all of these features in the confined space that is available between the gearbox and its cowling. A schematic of the sensor is shown in Figure 3.

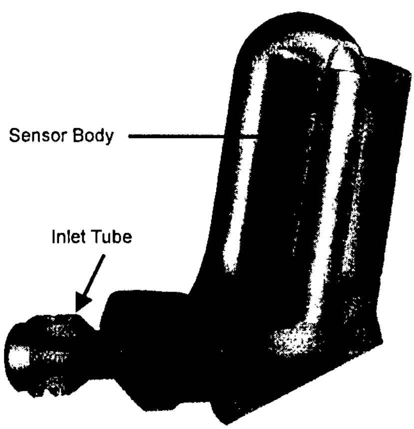

Figure 3: ODM Sensor Design

The oil enters the sensor at the inlet spigot which protrudes into the gearbox housing and seals the pump inlet cavity from the rest of the sump. This ensures that all of the oil flows through the sensor and maximizes the probability of debris detection. The oil flows through the inlet tube and around the outside of the sensor, in a cast passageway, and then into the body of the sensor where the sensing coils are located. To exit the sensor, the oil dumps into a cavity at the bottom of the sensor where it flows through an annulus around

the inlet tube, and back into the pump inlet cavity in the gearbox housing. The flow path is designed to minimize pressure losses through sensor to the extent possible.

The on-sensor electronics requires special attention to allow the sensor to operate in a high temperature environment. The electronics consists of a single circuit board which is installed in an aluminum housing bolted to the side of the sensor housing. Because of the low level of the signals transmitted between the coils and the electronics, it is necessary to minimize the distance between the coils and the circuit board. At the same time this results in the circuit being closer to the oil flow which is the primary source of heat flow to the electronics.

The electronics are designed to be air cooled, using airflow that is drawn over the gearbox during operation. To maximize the cooling, the hotter components of the circuit are placed in close proximity to the outer wall of the electronics housing and a thermally conductive potting material is used to bond the circuit to the housing. On the other side of the board, an insulating potting material is used to minimize the conduction of heat from the oil to the board. This design results in the sensor being able to operate in oil at 285 F with the electronics being maintained below 200 F with only moderate air flow over the sensor.

The AH-64 ODM sensor is shown in Figure 4.

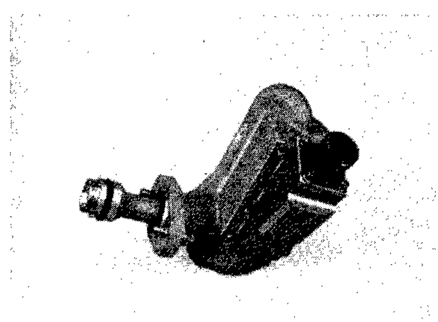

Figure 4: AH-64 ODM Sensor

Electronics Design: The particles of interest in diagnosing machinery problems are extremely small and therefore produce microvolt level signals as they pass through the ODM sensor. To reduce the complexity and cost of the cabling required between the sensor and controller, some of the electronics were built into the AH-64 ODM sensor itself as described above. This provided for a much simpler and more flexible installation suitable for a retrofit application, while maintaining sensitivity and tolerance to electromagnetic interference.

The on-sensor electronics regulate the input power to eliminate any external noise sources, generate signals necessary to energize the sensor, and process and amplify the sensor output to extract particle signature waveforms. These waveforms are transmitted back to a controller box through the same cable that powers the sensor.

The controller box (shown in Figure 5) contains a powerful TMS320 Digital Signal Processor (DSP) capable of simultaneously processing signals from four ODM sensors. The controller can be expanded to handle up to eight sensors by adding a second DSP board. The DSP continuously performs phase adjustment, filtering, and signature detection algorithms on all four channels. Any detected particles are sized, counted, and logged to an internal FLASH non-volatile memory. The DSP also calculates the estimated total accumulated mass for each sensor channel. External warning and alarm indicators are actuated based upon pre-determined mass limits. Data can be downloaded into a laptop computer on the ground to allow for analysis of the information collected.

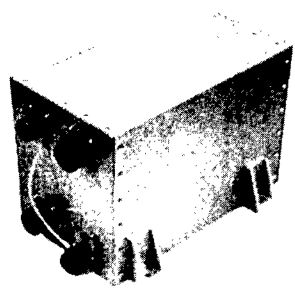

Figure 5: ODM Controller

The controller also performs periodic Built-In-Test cycles on the sensors. These tests are performed by injecting known signals into the system at the sensor itself and at the input to the controller box. This provides for a completed end-to-end test of the system as well as fault isolation.

Failure Progression Tests: In order to establish reliable criterion for warning, alarm or shutdown conditions based on the ODM output readings, a test program has been undertaken to investigate the failure of oil-wetted aircraft components. The goal of this program is to quantify the debris released from these components during failure and to evaluate the capability of the ODM to monitor failure progression.

To-date, tests have been conducted on a series of small diameter rolling element bearings as well as single tests on larger diameter bearings of conventional and hybrid designs. The results of these tests have been presented in previous publications [1, 2]. A summary of the test results are presented below.

Small Scale Bearing Tests: A large number of steel bearings (over 40 in total) have been run to failure in a test rig specially designed and instrumented for small scale (2 inch diameter) ball and roller bearings tests, as shown in Figure 6. The rig incorporates a fine mesh screen which captures the debris released during each failure for subsequent comparison to the ODM readings.

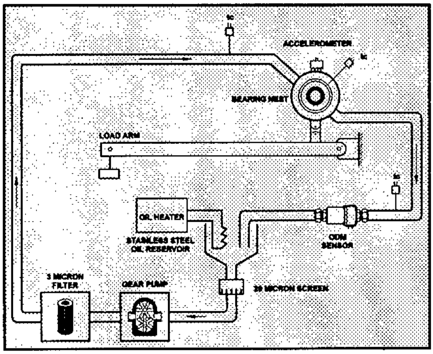

Figure 6: Bearing Test Rig

As illustrated in Figure 7, the sensor measurements indicate that large numbers of wear metal particles within the detectable size range of the sensor are released; starting with the first spall, continuing as the bearing is kept in operation and increasing in rate as damage reaches an advanced state.

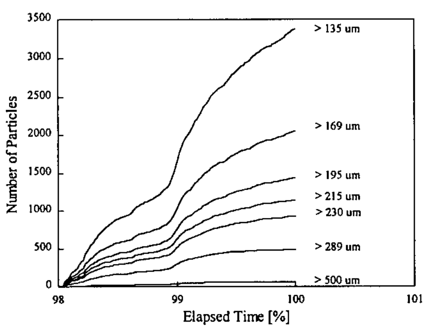

Figure 7: Small Diameter Bearing Test Results

Full Scale Bearing Test: A single test has been conducted by Pratt and Whitney on a large diameter thrust bearing from an aircraft engine application. The bearing material was steel and failure was initiated by intentionally damaging each of the functional surfaces of the bearing (inner race, outer race and balls) using 0.025 inch diameter

indents. Figure 8 shows the number of particles generated above each of the ferrous particle thresholds used for the test. As indicated, the sensor detected the initial spall and counted significant numbers of wear metal particles greater than 200 microns through the failure. In total, over 150,000 ferrous particles greater than 200 microns and more than 25,000 particles larger than 700 microns were counted. Also of note was the rapid increase in the rate of particles counted during the latter portion of the test.

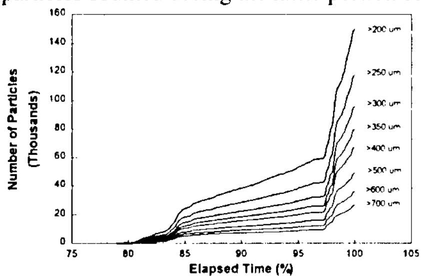

Figure 8: Large-Scale Bearing Test Results

Hybrid Bearing Test: A single test has also been conducted on an advanced technology hybrid bearing for aircraft engine application. Failure of this bearing, which incorporated ceramic balls and steel races, was initiated by a series of 0.02 inch diameter stress concentration pits created on the inner race of the bearing. Figure 9 shows the number of ferrous particles generated above each of the size thresholds used for the test. Once again, over the course of the test a large number of wear metal particles were counted by the sensor (over 7,000 particles greater than 200 microns and over 100 particles greater than 700 microns). As in the case of the large scale bearing test, a significant increase in the rate of particles counted during the latter stages of the failure was evident.

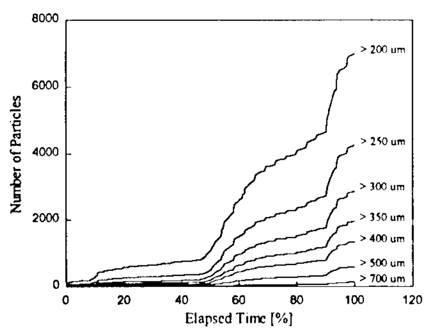

Figure 9: Hybrid Bearing Test Results

AH-64 Gearbox Rig Tests: Further testing of the AH-64 ODM system was conducted using a nose gearbox test rig located at the McDonnell Douglas facility in Phoenix, AZ. These tests were designed to verify the operation of the system in a simulated operational

environment. The tests encompassed both the speed and load ranges that cover the operational envelop of the AH-64 helicopter in static as well as dynamic conditions.

In addition to the operational tests, tests were conducted to evaluate the effectiveness of particle detection of the ODM system. This was achieved by "seeding" the gearbox with random samples of metallic particles through the gearbox breather port. The gearbox, with sensor installed, was run up to speed and load and the mass of particles mass detected by the system was noted. The gearbox was then shut down, the oil filter removed, cut apart and the debris ultrasonically extracted from the filter element. The total mass detected by the ODM was 67 mg versus 28 mg recovered from the filter itself. It is noted that the filter housing attached to the gearbox contained a significant number of metallic particles once the filter was removed; all of which must have passed through the ODM sensor but did not become lodged in the filter. It was not practical to extract these particles for weighing.

It was concluded by deductive inspection that the sum of the particles extracted from the filter plus the particles in the housing was likely close to the total mass detected by the sensor.

Summary: An in-line Oil Debris Monitor (ODM) has been successfully developed for the engine nose gearbox of the AH-64 helicopter. The ODM, designed as a direct on-for-one replacement of the existing magnetic chip detector system, is capable of reliably detecting both ferrous and non-ferrous wear metal particles under full flow conditions. The system has undergone pre-flight performance verification testing at McDonnell Douglas Helicopter Systems and is currently being evaluated on an operational AH-64.

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May, 1996

LASERNET Optical Oil Debris Monitor

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Abstract: The LASERNET optical oil debris monitor has been developed for real time on line identification of fault type and severity through detection of size, shape and rate of production of failure related debris in critical applications such as engines and gearboxes of helicopters. Detection of failure related debris without sampling has required the development of a high resolution high speed imaging and processing capable of recording and analyzing images at rates up to 500 frames per second. We have designed and constructed such a system based on parallel/series CCD technology, high speed dedicated image processors and neural net classifiers. The system has been tested on the T700 engine at the helicopter power train test cell at Naval Air Warfare Center, Trenton, NJ. Qualitative performance evaluation has demonstrated the ability to detect debris in real time and to distinguish and classify air bubble patterns in varying degrees of complexity. The overall false alarm rate depends on the strategy adopted in the image processor. For a dual processor architecture the results indicate that LASERNET will be capable of operating with a false alarm (defined as an incorrect identification of a rejectable gear box) rate of less than one every 2000 operating hours.

Key words: Bearings; early warning; catastrophic failure; gears; hydraulic fluid; real-time; shape classification

Introduction: Analysis of particle morphology has been shown to provide important capability in the identification of the type and severity of mechanical faults. [1-4] Currently most morphological studies are done in laboratories and involve analysis of oil samples drawn from the equipment. Real time on line detection and analysis of failure related debris in critical applications such as engines and gearboxes of helicopters can contribute to early detection and avoidance of potentially catastrophic conditions. Operating conditions, such as oil flow rates, and the infrequent production and relatively large size of failure related debris (generally greater than 100 μm) require that effective detection of failure related debris be done in a non-sampling full flow arrangement. Detection of failure related debris without sampling has required the development of a

high resolution high speed imaging and processing capable of recording and processing images at rates up to 500 frames per second.

LASERNET Description We have designed and constructed such a system based on parallel/series CCD technology, high speed dedicated image processors and neural net classifiers for fault identification. [5-9] The system has been tested on the T700 engine at the helicopter power train test cell at Naval Air Warfare Center, Trenton, NJ. A schematic of the system is shown in Fig. 1. It consists of a single mode diode laser operating at a wavelength of 830 nm, a flow adapter, a 512x512-pixel CCD imager, 512 x with a frame rate up to 1000- frames per second, and image processing electronics. The light transmitted through the viewing area of the flow adapter is imaged onto the CCD camera. Because of the speeds involved for framing and image processing, many conventional image processing approaches could not be used, and data reduction schemes had to be employed throughout the system. The uniformity of the laser illumination was

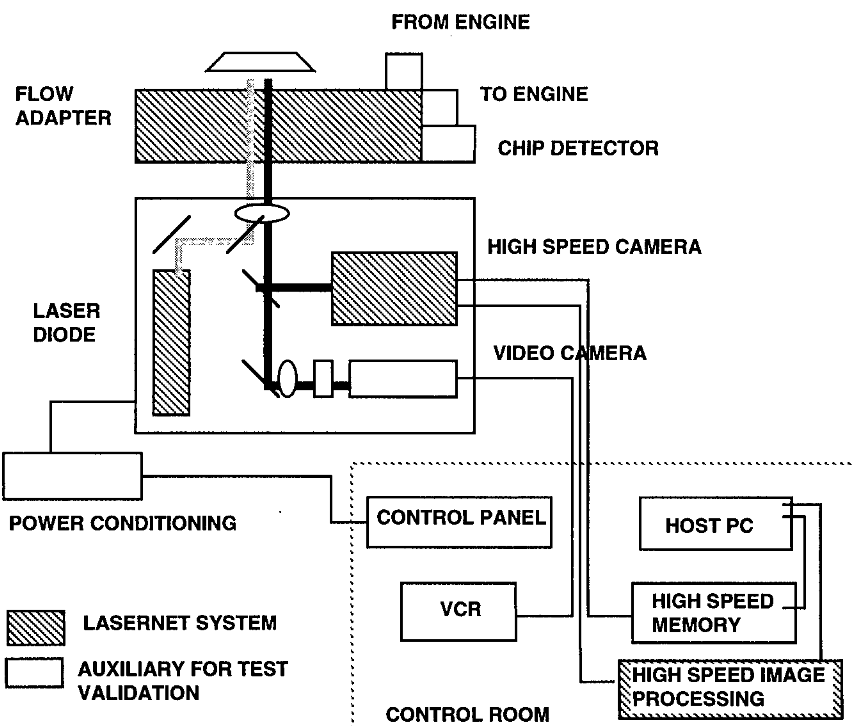

Fig. 1. Schematic diagram of the LASERNET test system for the T700 engine

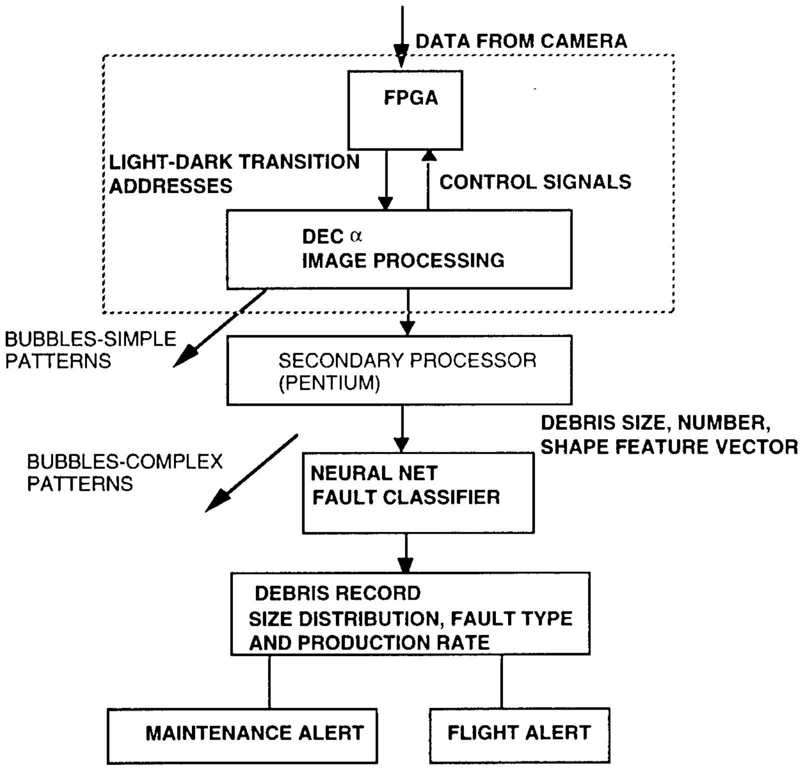

Fig. 2. Block diagram showing data flow in the image processor and fault classifier.

optimized, allowing a global threshold to be performed in the camera and one-bit image data to be transferred to the image processor.

A block diagram of the data flow in the processor is shown in Fig. 2. The data stream from the camera is held first in a full frame buffer. Pixels associated with edges of objects are identified in a field programmable gate array. The boundary pixels are assembled into individual objects in a DEC-alpha processor, and are then subjected to a series of shape identification tests. The processing strategy adopted was to identify air bubbles according to an ascending series of criteria, and to identify as debris all objects that failed the tests for bubbles. Bubbles were identified by a series of tests of increasing complexity, with objects that satisfied one level of test not being tested in subsequent

steps. As a result, increasingly complex tests were applied to fewer objects, minimizing overall processing times. The tests examined objects for circularity (single bubbles), double overlapping bubbles, and multiple bubble patterns. In order to meet the speed, false alarm, and debris detection requirements a dual processor architecture was adopted. Tests for single, double and simple multiple bubble patterns were done in the serial DEC-alpha, contained in the dotted box in Fig. 2. Objects that were not discarded were passed to a second processor, which performed detailed tests based on local curvatures to identify more complex bubble patterns. The tests performed in the DEC-alpha processor reduced the computational load for the secondary processor to a level of about one object per second. The performance of the resultant system was consistent with a false alarm (defined as an incorrect identification of a rejectable gear box) rate of less than one every 2000 operating hours.

Engine Tests: The system has been tested on the T700 engine at the helicopter power train test cell at Naval Air Warfare Center, Trenton, NJ under a variety of engine operating conditions. The flow adapter was connected to the engine at the auxiliary gearbox manifold in place of the existing chip detector. The chip detector was replaced in the system immediately after the viewing area of the flow adapter, providing the opportunity for visual comparison of the two detectors. The first set of tests were directed at demonstrating an acceptably low false alarm rate along with the ability to identify failure related debris. The test on the T700 engine was chosen for the low debris generation rate of the engine, providing a platform on which the false alarm rate could be examined under a variety of conditions. The system was operated at different engine conditions including ground and flight idle and a variety of applied torques. In order to train the classifier to distinguish various air bubble patterns from debris, images of bearing debris from a bearing test stand were introduced into images obtained from the high speed imaging system.

The results of these tests are summarized in Figs. 3 and 4. In Fig. 3 the evolution of the false alarm rate, defined as an incorrect identification of a rejectable gear box, is shown over the course of the tests. As time progressed, additional tests were introduced to handle increasingly complex bubble patterns as described above, and as these tests were introduced, the false alarm rate decreased. At the end of the tests a system showing zero false alarms was operating, with the corresponding rate shown in the figure.

The corresponding particle detection efficiency is shown in Fig. 4. Here, again the detection rate increased as the processing algorithms were improved. At the end of the tests the system was close to the target for the larger particles, but somewhat below the target for smaller particles. Further improvements can be obtained with the use of higher resolution cameras (1000 x 1000) that are now available.

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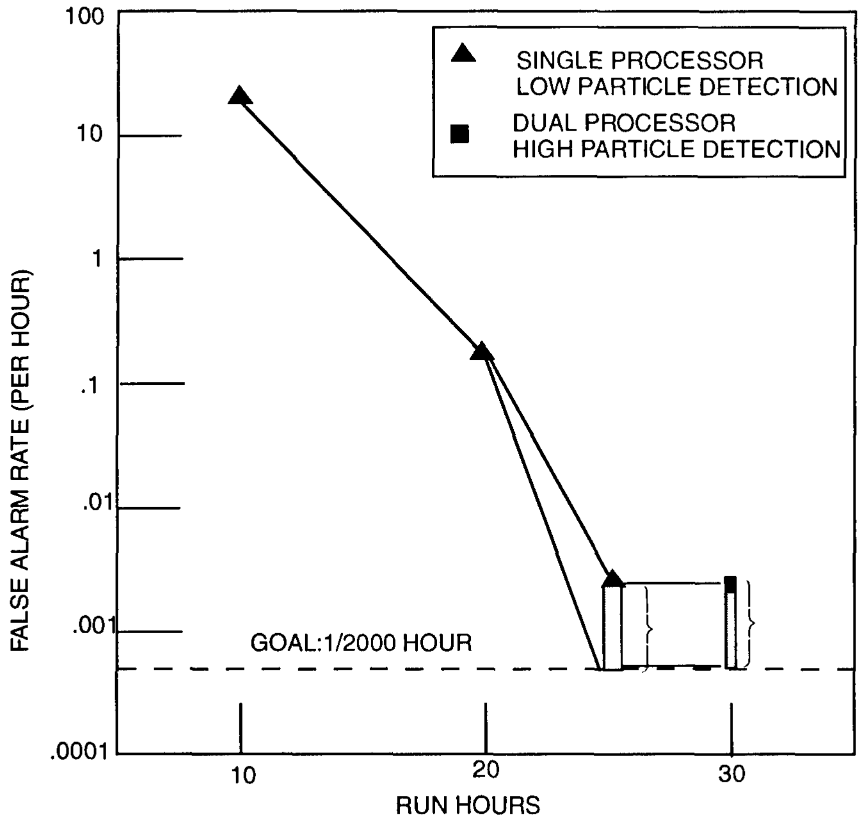

Fig. 3. False alarm rate progression for single and dual processor architecture. The brackets show the range of false alarm levels consistent with the demonstrated performance.

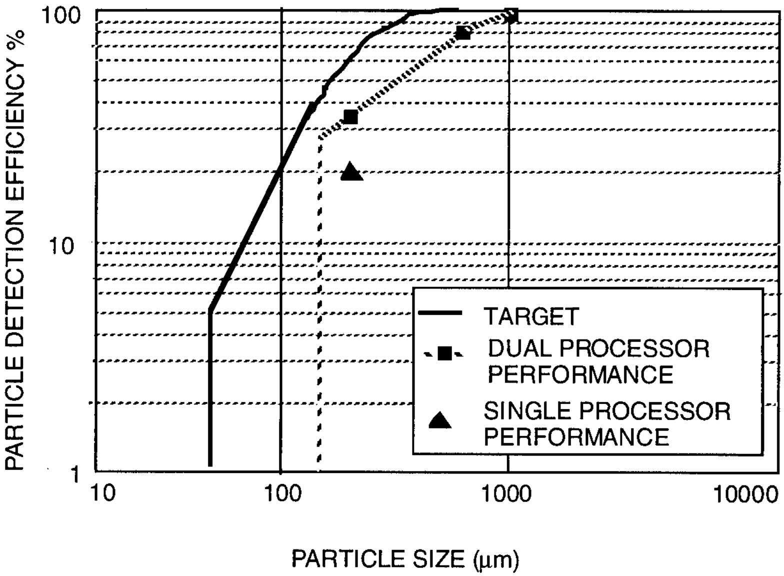

FIG. 4. Particle detection efficiency with single and dual processor architectures

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Abstract: The performance characteristics of the LASERNET FINES optical oil debris monitor are described. This monitor provides on-site measurements of particle size distributions and shape characteristics in lubricating, hydraulic and other fluids. It will provide information on mechanical wear of oil wetted machinery components and contamination in hydraulic systems. The features and capabilities of a portable instrument based on LASERNET FINES are described.

Key Words: Bearings; catastrophic failure; early warning; gears; hydraulic fluid; real-time; shape classification; wear debris

Introduction: LASERNET FINES is an optical oil debris monitor that is designed to provide real time measurements of size distributions and shape characteristics of particles in fluids in the size range from about 5 to 100 micrometers [1-5]. It will provide information on type, severity and rate of progression of specific faults and wear conditions in mechanical systems based on measurements of size distribution, shape and rate of production of debris particles [6-9]. This capability allows distinction of debris particles arising from different types of faults to be made and the progression of different

specific faults to be monitored. It will also provide information on particulate contamination in hydraulic, fuel and other fluid systems.

The basic concept of LASERNET FINES is illustrated in Fig. 1. The system uses a flowing fluid column that is back-illuminated with a pulsed single-spatial-mode laser diode to freeze the fluid motion. The light transmitted through the fluid is magnified and imaged onto a CCD camera. Some of the advantages of this technique are that flow speed does not have to be controlled other than being fast enough to clear the viewing area between laser pulses, and multiple particles in a single frame can be analyzed without confusion. The images obtained with the CCD camera are processed to identify individual objects. The objects are analyzed for size and various shape characteristics such as aspect ratio, circularity and edge roughness. The number and size of particles greater than about 5 micrometers and the shape characteristics of particles larger than about 20 micrometers are determined. The shape characteristics are used to classify the particles into mechanical wear classes such as cutting, sliding and fatigue with a neural net shape classifier. Each laser pulse provides a single image frame to be analyzed and the results of multiple frames are combined to form a complete record for the sample under study.

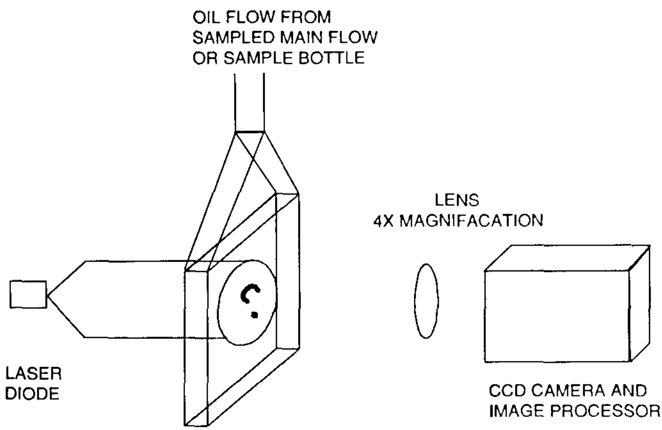

Figure 1. Schematic diagram of LASERNET FINES

LASERNET FINES can be configured as a batch processor, in which samples drawn from the machinery are analyzed off-line, as a temporary on-line unit or a dedicated on-line unit. The batch processor is appropriate for use in applications in which many different types of machinery are to be analyzed with one unit. It can eliminate the long turn around time associated with remote laboratory analysis. The temporary on-line unit is appropriate for use with problem equipment or for fleet utilization. The permanent on-line unit can provide continuous, autonomous monitoring that can provide early warning

and trending information for identifying fault progression and contribute to condition based maintenance and reduced manpower situations.

LASERNET FINES is being developed under the Condition Based Maintenance Program of the Office of Naval Research (ONR) by a team involving Naval Research Laboratory, Lockheed Martin Tactical Defense systems and Predict/DLI. The basic technology capabilities are being developed at NRL, while Lockheed Martin and Predict/DLI are producing a portable batch processor for field applications based on the LASERNET FINES technology under contract to ONR.

Technology Development: The initial efforts at NRL have been directed at demonstrating the basic technology in a batch processor format. The unit consists of a collimated single-spatial laser diode, a flow cell, 4X magnification imaging optics, progressive scan camera, and computer with frame grabber. The laser diode operates at 820 nm with a peak power of 27 mW. The laser is pulsed with a duration between 5 and 350 μs depending upon the transparancy of the fluid being analyzed. The flow cell is approximately 100 μm thick with a fluid reservoir mounted above the cell. Fluid is drawn through the flow cell with a peristaltic pump. Before a sample is analyzed, the fluid is shaken for 30 seconds to disperse the particles and is then placed in an ultrasonic bath for 45 seconds to remove trapped air bubbles. This preparation method has been observed to give consistent results over several identical samples. The imaging optics relay a 1.6 mm x 1.2 mm area of the flow cell flow onto the CCD camera at a 4X magnification with a spatial resolution of about 2.5 micrometers. The images are transferred to a computer and are analyzed at a rate of 7 frames per second.

The images undergo a pixel-by-pixel subtraction of a background image and are thresholded. The thresholded image is scanned in a raster format following the method of Capson (10) to identify particle objects. The particles are analyzed to determine the following features: maximum diameter and area for all objects, and aspect ratio (defined as area / maximum diameter ^2), perimeter, and circularity for particles greater than 20 μm in diameter.

The particles are classified into fatigue, sliding and cutting wear using a linear vector quantization neural net and specific shape features. The classifier was trained with a set of wear particles images of known origin that were provided by Predict/DLI and by University of Swansea, Wales, UK. The classifier had about a 90% success rate in placing the particles from the training set into the correct wear category.

The LASERNET FINES bench unit was used to examine several different types of fluid that are expected to be encountered in shipboard machinery. We present below results obtained for hydraulic calibration fluid, obtained from Fluid Technologies, Inc., and for MIL-L-9000 diesel lubricant. The results of the measurements of the concentration of particles in the hydraulic calibration fluid are shown in Fig. 2. The distribution of particle concentration is shown as a function of maximum linear dimension in NAS size bins (5-15 μm, 15-25 μm, 25-50 μm, > 50 μm) for two runs with the LASERNET FINES unit,

along with the concentrations given by FTI. The agreement is quite good for the smaller three bins, with larger deviations seen in the largest bin, which are likely due to statistical fluctuations because of the small number of large particles in the samples.

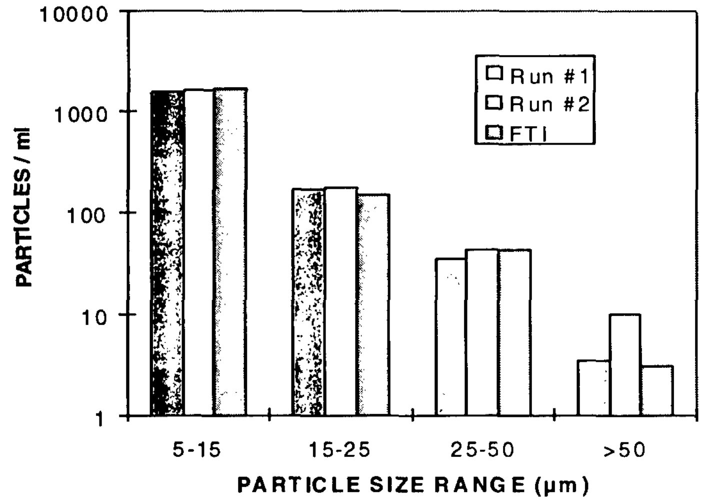

Figure 2. Measured particle distribution for two runs by LASERNET FINES instrument compared to particle distribution provided by Fluid Technologies Inc. Measured sample volumes are: 2.25 ml for Run 1, 1.5 ml for Run 2.

Several samples of MIL-L-9000 from equipment aboard the USS Gunston Hall were also analyzed, with the results shown in Fig. 3. The transmissivity of these samples in our viewing cell varied over 3 orders of magnitude, from 80% to less than 0.001%. These results show a consistently large concentrations of particles in the size range from 5-15 μm, with considerable variability of concentration in the larger size ranges. Correlation of these results with other analysis techniques is in progress.

Instrument Development: Under a contract with the Office of Naval Research (ONR), Lockheed Martin Tactical Defense Systems – Akron has developed a batch instrument based on the LASERNET FINES technology to analyze fluid samples for the wear debris particles. A photograph of the instrument is shown in Fig. 4. The instrument was designed to fit the Navy's need for a shipboard system which analyzes wear debris to help determine machine condition. The instrument analyzes particles in the size range of 5 to 100 microns and produces a statistically accurate result in 7 minutes. It counts and calculates size trends for particles based on size over the complete size range. Using a neural net classifier, it also identifies particles by wear type in the size range of 20 to 100

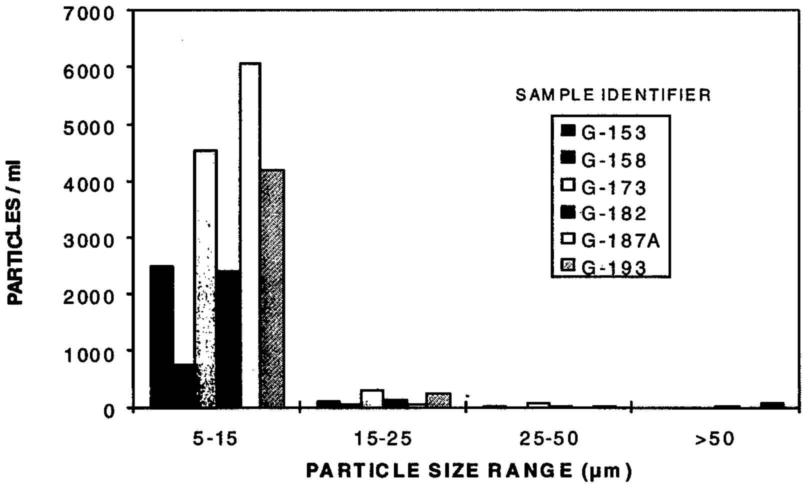

Figure 3. Particle size distribution for several samples of MIL-L-9000 diesel lubricant

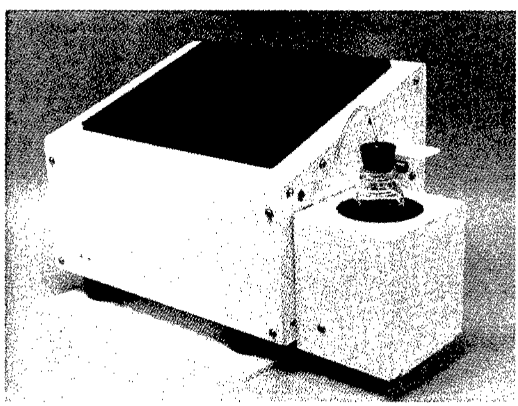

Figure 4. Photograph of Lockheed Martin Optical Oil Debris Monitor

microns. Three classes of particles are identified: fatigue, severe sliding wear, and cutting wear. Based upon the information gathered on particle concentration, sizes, trends, and types, a machine condition can be determined.

Figure 5 shows the basic functions of the system. Fluids are processed in batches. Fluid from a sample bottle is drawn into the instrument using a sipper arrangement and a peristaltic pump. The fluid is pumped through an optically transparent flow cell. Coherent light from a pulsed laser diode is used to back-illuminate the sample, while a CCD camera with macro focusing optics images the sample 30 times per second. A Pentium-based processor with a frame grabber card digitizes the resulting images and performs all processing functions. The results are displayed on a color LCD display with touch panel interface.

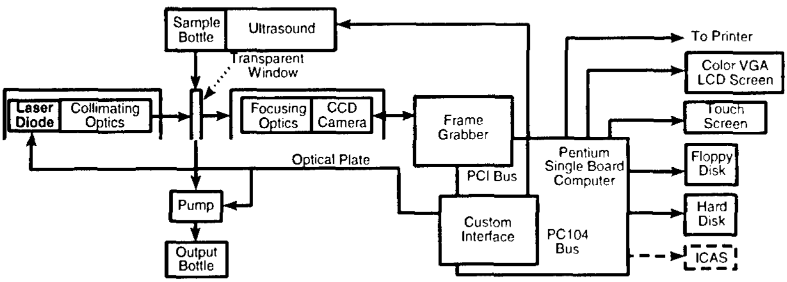

Figure 5. Block diagram of the Lockheed Martin Optical Oil Debris Monitor

The instrument was designed to be compatible with shipboard operation. It requires 110 VAC 60Hz power. Its volume is about 1 ¼" cubic feet and it weighs about 35 pounds. To help protect the unit from external shock and vibration, the unit is isolated from the base plate with shock mounts.

The instrument was designed to interface with a centralized computer system such as the Integrated Condition Assessment system (ICAS) that is available aboard some US Navy ships. The physical interface used is a 10 Mbit/sec Ethernet. Using the Windows network file system protocol, information is passed to the ICAS by writing a series of files to a directory mounted on the ICAS system. This data is transferred to ICAS after every oil test is performed and includes information on the results of the test as well as information on the machine under test and where the sample was taken.

In the design of this instrument special emphasis was given to the user interface. A graphical user interface based upon a series of about 30 context specific menus was developed to guide a user through the various functions that can be performed. A touch screen over the color LCD display is used for input of information into the system. The touch screen used in conjunction with the menuing system simplifies the input process by guiding the user's choices at each stage of the process. The graphical user interface is based upon Windows NT's windowing environment. When possible, the user is presented with scrolling lists of options to choose from. Most data fields have up/down buttons for incrementing or decrementing through values. When specific fields of data

need to be entered, the user is guided through the process by the computer highlighting the specific fields in the color, yellow. In the case, when the standard set of slide bars, and scrolls lists are not of the appropriate form for receiving data from a user, a standard keyboard is presented on the display for use. In these situations, before it is presented, a list of past inputs is presented for use. Only if this past data is not appropriate, will a keyboard be presented. A picture of the starting menu screen is shown in Fig. 6, while a picture of one of several results screens is shown in Fig. 7.

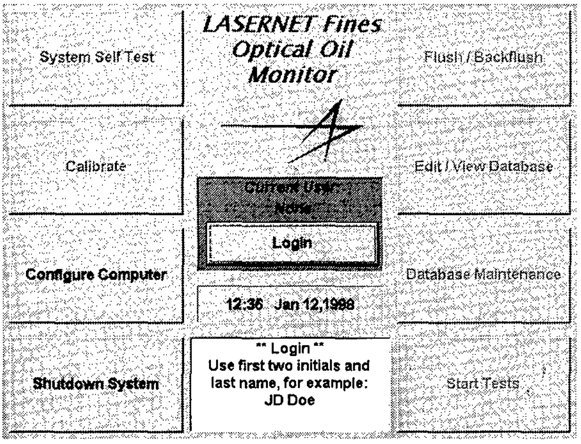

Figure 6 Example of the startup screen from the user interface, showing user options for running sample tests or other operations.

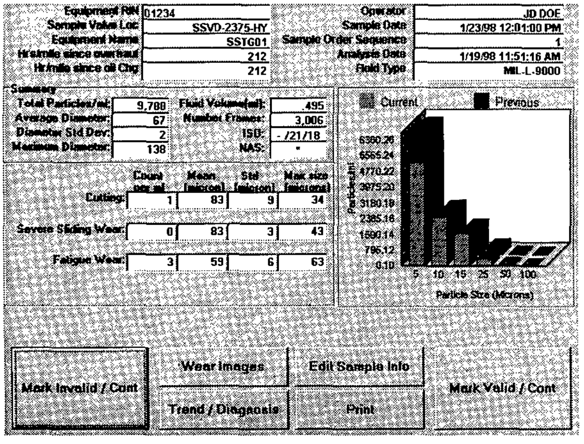

Figure 7. Example of one of the results screens showing the type of information provided.

Acknowledgment: This work was supported by the Office of Naval Research.

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A Computerised Wear Particle Atlas for Ferrogram and Filtergram Analyses

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Abstract: A new computerised wear particle atlas has been developed for identification of solid particles and differentiation of wear severity of lubricated equipment. This atlas contains 892 images of representative solid particles selected from thousands of filtergram and ferrogram slides, enabling to cover diverse ferrous, nonferrous and contaminant particles in used lubricants. The unique wear severity differentiation atlas, which combines measurable particle parameters with comparable particle images, significantly benefits standard wear particle analysis.

key Words: Condition Monitoring; ferrogram; filtergram; particle images; wear particle; wear particle atlas; wear severity level.

1. Introduction: A wear particle atlas is probably the most valuable reference for microscopic wear particle analysis. The first wear particle atlas, which was developed in 1976 [1] and revised in 1983 [2], has significantly contributed to application and development of wear particle analysis in machine condition monitoring. However, as this atlas mainly focuses on identification of the solid particles separated by ferrogram method (i.e., Analytical Ferrograph), its role in guiding wear condition monitoring is restricted. To develop a new wear particle atlas is thus increasingly indispensable based on the following considerations:

- Recently, various non-magnetic particle separation methods, such as the filtergram method (using cellulous filter membrane) developed by Monash University [3] and the filter-based back-flush method from the pore-blockage particle counter sensor [4], etc, have been used to strengthen wear particle analysis. Because the visible features of solid particles between the two separation methods, such as position, orientation and sizing etc, are often dissimilar due to different particle separation principles, the identification guidelines for ferrogram particles are not appropriate to filter-based methods (in general, filtergram method).

- Microscopic wear particle analysis is still a qualitative and non-standard operation. In particular, differentiation of machine wear severity levels based on wear particle analysis is currently an entirely person-dependant activity [5]. It is not unusual that different analysts could make inconsistent judgements on the wear severity level of same oil sample, resulting in high risk factor in machine condition monitoring and

difficulty in data/information communication. Though it is far from establishing a quantitative standard for wear severity differentiation using automated image analysis technology, a well-developed wear particle atlas seems to be still able to improve consistency of wear particle analysis significantly. To develop a wear severity differentiation atlas, which combines measurable and important particle parameters with visible and comparable particle images to illustrate sequential wear processes, will be a cost effective alternative.

Application of various software packages in oil & wear debris analysis and lubrication maintenance has demanded a computerised wear particle atlas for more efficient image comparison and correlation analysis. Remarkable development in PC and data storage technologies has also enabled thousands of colour images to be recorded on a CD disk with low cost.

Based on the expertise in both ferrogram and filtergram wear particle analyses during the past decades, ***Lubrosoft*** has developed a computerised wear particle atlas (called Wear Particle Atlas 97) to meet the advanced requirements above.

2. Hierarchy: Wear Particle Atlas 97 covers three main categories of solid particles in lubricants, i.e., Contaminant Particles, Nonferrous Wear Particles and Ferrous Wear Particles. The hierarchy of the atlas is shown in Table 1-3.

Table 1 Contaminant Particles

1.1 Contaminants	1.2 Contamination Level
1.1.1 Silica Dusts - Filtergram & Ferrogram 1.1.2 Carbon Dusts - Filtergram & Ferrogram 1.1.3 Ferrous Oxides - Filtergram & Ferrogram 1.1.4 Fibre - Filtergram only 1.1.5 Soft Compounds - Filtergram & Ferrogram 1.1.6 Corrosive Particles - Ferrogram only	Level 1 ...... Level 10

Table 2 Nonferrous Wear Particles

2.1 Materials	2.2 Wear Modes	2.3 Wear Severity
2.1.1 Copper Alloy 2.1.2 Aluminium Alloy 2.1.3 Lead/Tin Alloy	2.2.1 Rubbing Wear 2.2.2 Cutting Wear 2.2.3 Fatigue Wear 2.2.4 Sliding Wear	Level 1 .... Level 10

Table 3 Ferrous Wear Particle

3.1 Materials	3.2 Particle Modes	3.3 Wear-Mode-Related Severity
3.1.1 Cast Iron 3.1.2 Low Alloy Steel 3.1.3 High Alloy Steel	3.2.1 Rubbing Wear 3.2.2 Cutting Wear 3.2.3 Fatigue Wear 3.3.4 Sliding Wear 3.3.5 Combined Sliding and Fatigue Wear	3.3.1 Rubbing Wear Severity 3.3.2 Cutting Wear Severity 3.3.3 Fatigue Wear Severity 3.3.4 Sliding Wear Severity 3.3.5 Combined Wear Severity

A total of 8 sub-categories, which contains 892 representative colour particle images, cover a wide range of wear conditions of lubricated equipment. A total of 14 graphic interfaces are employed to guide particle identification and search more efficiently. While opening the atlas, Home Page (Fig 1) will appear firstly, in which 8 wear particle images are representative of 8 sub-categories of solid particles respectively. Through clicking each image, the correspondent sub-category pages, which also contain representative particle images to represent each sub-sub-category, will occur. For instance, clicking the image labelled as "Nonferrous Materials" from Home Page, the Nonferrous Material sub-page, which contains 3 typical nonferrous metal particle images of representing Copper, Aluminium and Lead/Tin alloys respectively, will appear (Fig 2). Further clicking the image labelled as Copper-Ferrogram, the working page (Fig 3) will appear to show the various images of the copper metal wear particles separated by ferrogram method.

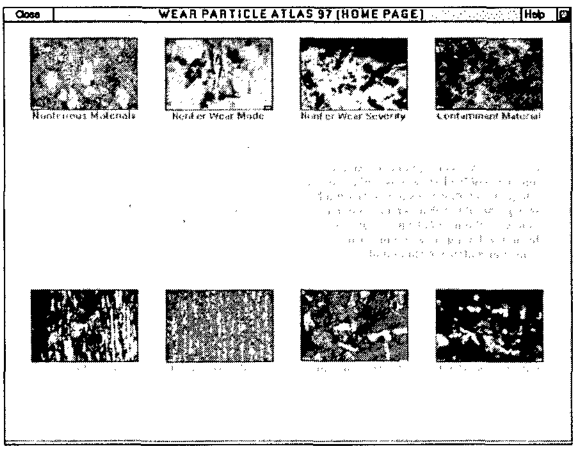

Fig 1 Home Page

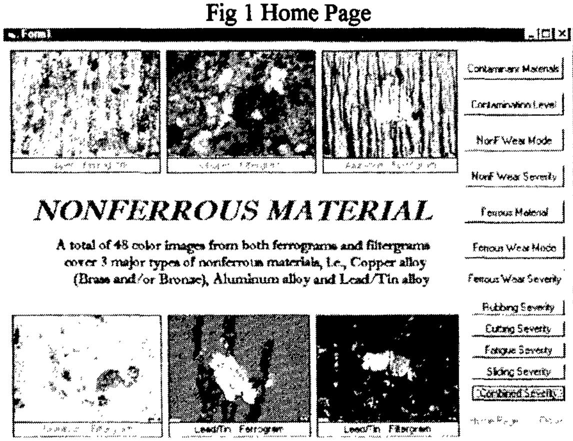

Fig 2 Sub-category - Nonferrous Materials

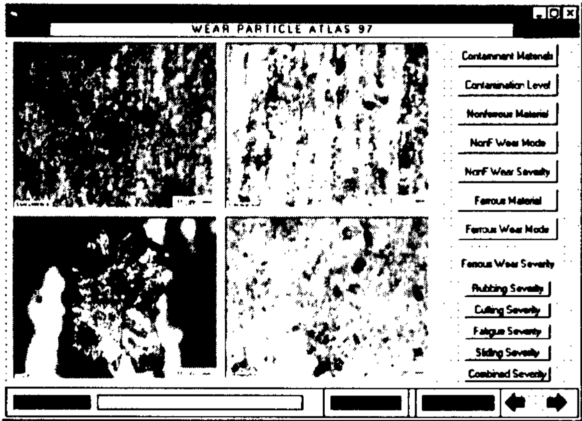

Fig 3 Working page

3. Characteristics

3.1 Complementary Integration of Two Particle Separation Methods: The ferrogram method is excellent in identifying materials of solid particles but deficient in collecting nonferrous particles, whereas the filtergram method is prominent in collecting all solid particles larger than the pore size of the filter membrane but restricted in identifying materials of solid particles. Wear Particle Atlas 97 exclusively embraces the solid particles from both filtergram and ferrogram methods, enabling to compensate their respective limitations to maximise the strengths of microscopic wear particle analysis.

Fig 4 (a) shows an easy-to-identify nonferrous wear particle image on a ferrogram slide. The non-magnetic deposition pattern of the white metal particles on this ferrogram slide makes them to be discriminated from the ferrous particles easily. As colour and brightness of both ferrous and white metal particles are very similar and lack of depositing orientation and locations as on a ferrogram, it is very difficult to identify these nonferrous particles from the ferrous particles while they are on the filtergram slide, see Fig 4 (b)

Fig 4 (a) Lead/Ton particles on a ferrogram

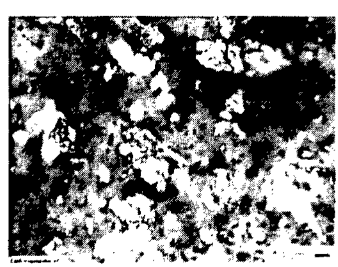

Fig 4 (b) Lead/Tin particles on a filtergram

On the other hand, however, the filtergram method can collect nonferrous metal particles with high efficiency, showing a high reliability in detecting wear condition of nonferrous components. Fig 5 (a) shows the massive rubbing copper wear particles on a filtergram slide from a worm gearbox, revealing a high wear rate of the copper worm gear. But the ferrogram, which is made of same volume of oil sample, shows a very low copper particle concentration, see Fig 5 (b). It is estimated that the collecting efficiency of ferrogram method for small copper particles is likely to be less than 10% in this case.

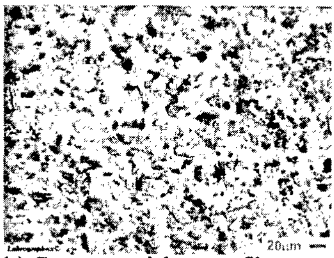

Fig 5 (a) Copper particles on a filtergram

Fig 5 (b) Copper particles on a ferrogram

3.2 Atlas for Wear Severity Differentiation: Wear Particle Atlas 97 provides an exclusive filtergram-based wear severity differentiation component to assist judgement of machine wear severity levels with improved consistency. This component consists of a total 456 images and 121 application cases (i.e., examples). The wear severity levels are divided into either 10 levels for nonferrous component wear and ferrous rubbing wear mode (from Level 1 to Level 10) or 8 levels for those 'abnormal' ferrous wear modes (from Level 3 to Level 10), indicating wear deterioration processes from an initial wear up to a severe wear condition.

To improve the consistency of wear severity differentiation, the atlas firstly defines the "key features" for each severity level, which are the quantitative, measurable criteria based on size distributions and wear-mode-related type distributions of wear particles. Secondly, the atlas provides 1-5 wear particle examples at each severity level which approximately meet the criteria of the designated severity level. Each example consists of 4 representative wear particle images. By matching both measurable criteria and visible images, a random wear particle sample can be coded with a certain severity level.

For example, by means of the atlas, the metal particles of an oil sample are identified as:

- ferrous fatigue wear particles;
- the size of the fatigue wear particles is up to 100μm, and
- the concentration of the fatigue wear particles ranging between 50-100μm in size is about 60-80/ml.

These identified features match the designated criteria of Level 6 of ferrous fatigue wear severity as shown as follows:

- Up to **<u>100μm</u>** in size;

- Predominant laminar particles; and
- Concentration of laminar particles ranging between **50-100μm**: **>100/ml**

Further, the features of the wear particles of this sample are similar to those of the application cases (i.e., examples) of Level 6 in the atlas, see Fig 6. Therefore, the wear severity level of this oil sample can be differentiated as Level 6.

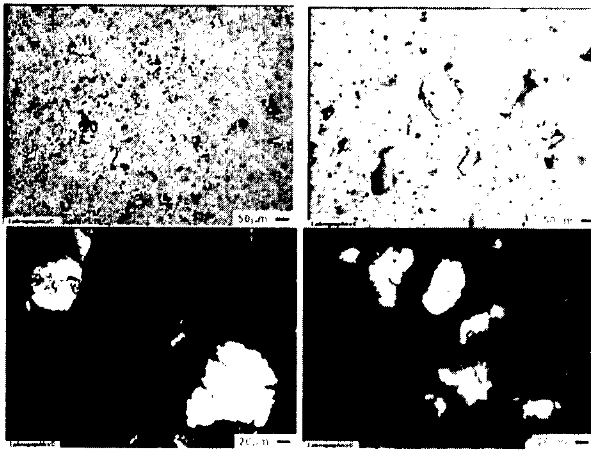

Fig 6 (a) Example 1 of fatigue severity level 6

This differentiated level, however, is a universal wear severity level. Depending on the criticality, operation environment and expected life of this machine, etc, this universal severity level may be defined as a "normal" or an "abnormal" or even a catastrophic condition. For example, if this sample is taken from an uncritical gearbox operated under a highly contaminated environment with a low design life, this severity level (Level 6) may be defined as a "mildly abnormal" wear condition. However, if this sample is taken from a critical hydraulic system, this level 6 may be specified as an "unacceptable" or even a "severe" condition. It is from this sense that the wear severity differentiation atlas provides an approximate yardstick of measuring wear severity levels of lubricated equipment, significantly contributing to consistent and standardised wear particle analysis.

3.3 Cleanliness Identification Of Lubricant: Wear Particle Atlas 97 also provides an ISO Cleanliness - Contaminant concentration reference for lubricant contamination monitoring. This reference consists of 10 sequential ISO Cleanliness levels from ISO 13/10 up to ISO 24/21, see Table 4. Each level contains 4 representative solid particle images grabbed from different areas of the filtergram with varied magnifications. This component can be used to correlate machine wear with lubricant contamination, and to estimate the cleanliness code numbers of some very dirty and/or water contaminated oil samples, which are usually unavailable or inconvenient for automatic particle counting. Fig 7 shows the solid particles corresponding to ISO cleanliness 19/16.

Table 4 Contamination levels and correspondent ISO Cleanliness

Contamination Level	ISO Cleanliness
Level 1	ISO13/10
Level 2	ISO15/12
Level 3	ISO16/13
Level 4	ISO17/14
Level 5	ISO18/15
Level 6	ISO19/16
Level 7	ISO20/17
Level 8	ISO21/18
Level 9	ISO22/19
Level 10	ISO24/21

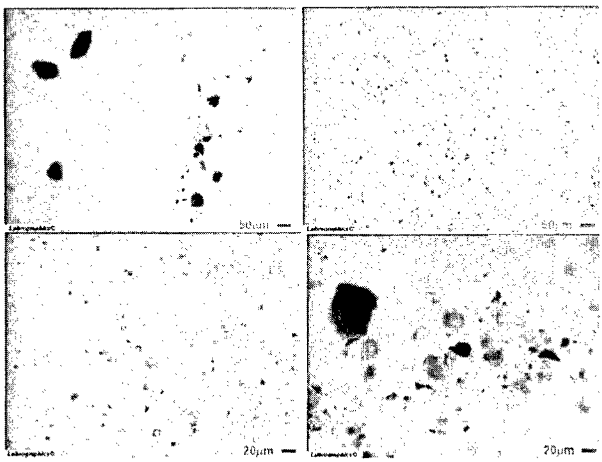

Fig 7 Solid particles on the filtergram slide corresponding to ISO Cleanliness 19/16

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Wear Particle Analysis Results for Variably Loaded Single Reduction Helical Gearboxes

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Abstract: The Mechanical Diagnostic Test Bed (MDTB) was constructed as a multi-sensor instrumented gear/transmission test stand by the Pennsylvania State University in the area of Condition-Based Maintenance (CBM). The MDTB data acquisition system is capable of recording (using PC-LabWindows) transitional run-to-failure data sets from a variety of commensurate and non-commensurate (vibration, oil, temperature, and acoustic emission) sensors. Off-line JOAP oil analysis results (ferrography) for samples collected from industrial grade (off-the-shelf) single-pair helical gearboxes subjected to sustained output loads of 2-3 times their rated maximum torque are presented.

The off-line oil ferrography results indicated a much higher sliding and cutting wear particle content for the higher loaded (3X maximum torque) experiments. This agrees with intuition. One of the goals of this research is to fuse oil sensor information on lubricant condition in an on-line manner with vibration (accelerometer) data as well as with acoustic emission and thermographic sensor data in order to effectively detect developing or incipient faults, and to predict (with confidence bounds) the remaining useful life of the system (gearbox).

Keywords: Condition monitoring; helical gears; transitional data; ferrography; fusion; MDTB; lubricant condition.

Introduction: One of the principal goals of CBM is the development of the capability to accurately predict remaining useful life of a critical component or system without interrupting operational time for inspections. A successful integration of this kind of (CBM) technology within an overall maintenance program promises to result in increased cost savings, machine usage, and human safety. At this point, the benefits of oil analysis for condition monitoring have been well-documented [2] and need not be repeated here.

Motivation for the Mechanical Diagnostics Test Bed (MDTB): Methods in maintenance technology are constantly evolving. A multitude of new technologies has been applied to the maintenance and mechanical diagnostics problem. Examples include advanced detection methods for temperature, oil analysis, and vibration signals. A limiting factor in the further development of CBM has been a lack of high-fidelity data of faults as they initiate and evolve. This shortcoming is addressed by the MDTB effort to provide a realistic test stand that effectively represents an operational environment while bridging the chasm between typical university-scale test facilities and industrial-scale applications. The MDTB directly accommodates the need for transitional data that tracks faults from initiation to an ultimate failure mode by including oil analysis.

MDTB Description - General Overview: The MDTB, shown in Figure 1 below, is functionally a motor-drivetrain-generator test stand. The gearbox is driven by a 30 Hp AC (driver) motor, while torque is applied by a 75 Hp AC (absorption) motor. The system speed and torque set points are produced by analog input signals supplied by the Data Acquisition Computer. Shafts are connected with tandem flexible and rigid couplings. Torque-limiting shear couples are used on both sides of the gearbox to prevent transmission of excessive torque as could occur with gear jam or bearing seizure. Furthermore, torque cells are used on both sides of the gearbox to directly monitor efficiency and the loads transmitted. The MDTB has the capability of testing single and double reduction industrial gearboxes with ratios from about 1.2:1 to 6:1, and are nominally in the 5-20 Hp range.

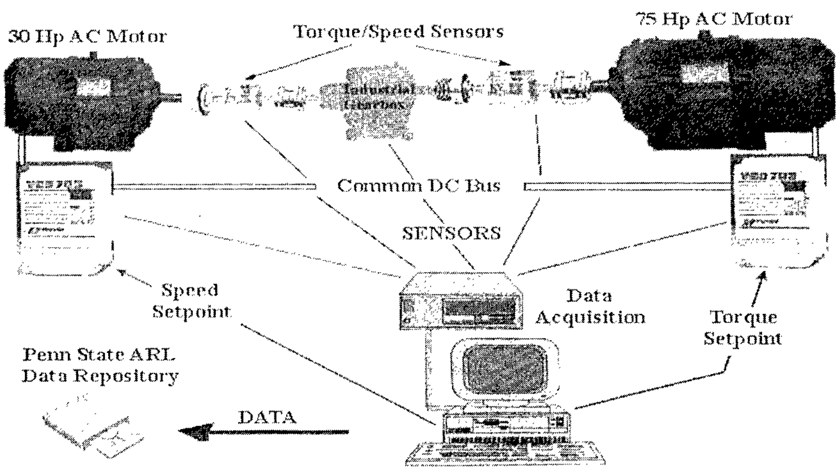

Figure 1. Mechanical Diagnostics Test Bed

Status: Ten gearboxes have been run to failure on the MDTB. These were all single reduction 10 Hp industrial gearboxes. They contain a single pair of helical gears with a gear ratio of 1.5:1, i.e., 30-tooth pinion / 46-tooth output gear, with ball bearings on the input shaft and tapered roller bearings on the output shaft.

The first run was primarily a shakedown run resulting in a tooth breakage failure from first running the gearbox at twice its rated torque for ten days and three times its rated torque for an additional eleven hours. The final result was a complete decoupling of input and output shafts due to severe tooth breakage.

The second through sixth gearboxes were all run under the same load conditions. Each was first run at its rated speed and torque for four days (break-in period), and then loaded to three times its rated torque at rated speed until failure. The point of failure was established as at least two accelerometers exceeding 150% of their nominal RMS vibration level. In all five cases, the final result was tooth breakage. The seventh through tenth gearboxes were run in the same manner, except that after the break-in period they were loaded to twice their rated torque. Figure 2 shows the total overload period run times for the nine gearboxes.

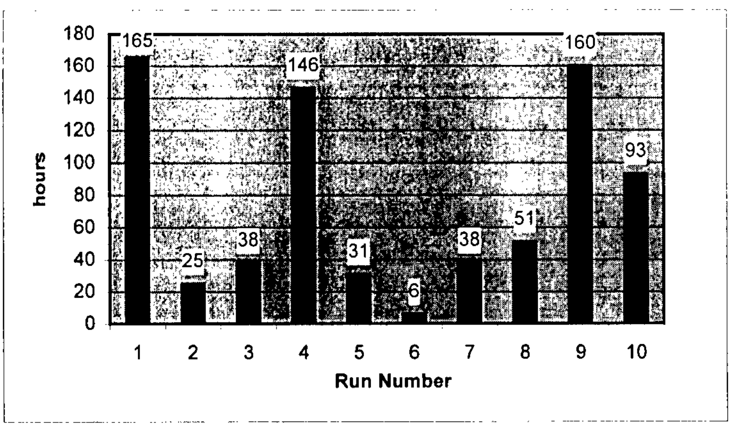

Figure 2. Loaded Gearbox Run Time

The mean (μ) and sample standard deviations (s) in hours on load for runs 2-6 (3X output torque load) and runs 7-10 (2X output torque load) were (μ = 49.2, s = 55.4) and (μ = 85.5, s = 54.9), respectively. Note that lower output torque loading (runs 7-10 above in Fig. 2) results in longer time-to-failure on average. This agrees with intuition. However, the variance in run times is relatively high and approximately equal for both load conditions. It is a coincidence that the third run of each set (#4 vs. #9) has the longest

time-to-failure for each set. One can not draw statistically significant conclusions from this data – which is presented here, but is used to illustrate the approach on which we are embarking.

Oil Sampling and Analysis: After MDTB shutdown and suspected gear-tooth failure, approximately 8 oz of the lubricant (oil type Mobile SHC 634) is collected as soon as possible from the gearbox well and mailed to the Joint Oil Analysis Program (JOAP) for analysis. At the beginning of these experiments, a clean test sample of the same oil was submitted to the JOAP to serve as a baseline sample. Tables 1 and 2 below represent both the post-mortem gearbox damage autopsy and ferrography results to date.

The Direct Reading Ferrography (DRF) procedure carried out measures the amount of magnetic particle wear debris from the sample, evaluating it with respect to typical ferrographic wear particles based on type, size and quantity.

<table>
<tr><th colspan="6">3X Loading</th><th colspan="3">2X Loading</th></tr>
<tr><th>Part</th><th>Run 2</th><th>Run 3</th><th>Run 4</th><th>Run 5</th><th>Run 6</th><th>Run 7</th><th>Run 8</th><th>Run 9</th></tr>
<tr><td>Drive Gear</td><td>Tooth Failures</td><td>Tooth Failures</td><td>Tooth Failures</td><td>Tooth Failures</td><td>Tooth Failures</td><td>Tooth Failures</td><td>Tooth Failures</td><td>Tooth Failures</td></tr>
<tr><td>Input Ball Bearings</td><td>Scoring Pitting</td><td>Scoring</td><td>Scoring</td><td>Scoring</td><td>Scoring</td><td>Scoring</td><td>Scoring</td><td>Scoring</td></tr>
<tr><td>Output Roller Bearings</td><td>Scoring</td><td>Scoring</td><td>Scoring</td><td>Scoring</td><td>Scoring Damaged Inner Race</td><td>Scoring</td><td>Scoring</td><td>Scoring</td></tr>
</table>

Table I. Autopsy of MDTB Gearboxes

	3X Loading					2X Loading		
DR Ferrography	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
Rubbing Wear (rdn)	4	3	4	4	4	4	4	4
Sliding Wear (rdn) Size (microns)	3 50	3 70	4	4 120	4 120	4 40	3 80	3 90
Cutting Wear (rdn) Size (microns)				2 60		3 10		
Laminar Wear (rdn) Size (microns)	3 62	3 70	4 130					
Black Oxides (rdn)		3			3	4	3	3

Table II. Direct Reading Ferrography

Table I lists the observed post-mortem faults for the gearbox in question for each run. Essentially, Table 1 is self-explanatory. Tooth failure here means at least one (and usually two side-by-side) broken gear-teeth. The contact ratio for the helical gears in the experiment was approximately 2.1.

Table II lists the DRF results in relative units specific to the JOAP Laboratory. For example, in the row labeled "sliding wear," the numbers 3 and 4 are so-called "rdn" or relative density values. These numbers range from 0 – 4, with 0 = no particle and 4 = maximum level for the given equipment. The rdn ranges may be different from lab to lab. Some labs use a 0 – 10 scale. The remaining lower numbers such as 50, 70, 120, etc., (where provided) indicate the size (in microns) of the particles observed.

For Run #4, the gearbox lasted 146 hrs (Figure 2) while operating under a 3Xs maximum output torque condition. After failure the gearbox was disassembled and two broken gear teeth were seen as well scoring on both input ball and output roller bearings (Table I). Oil analysis indicated large quantities for particles resulting from Rubbing Wear, Sliding Wear, and Laminar Wear (Table II).

As expected, indicators for rubbing wear and sliding wear occurred in every case. Rubbing wear is a universal manifestation of normal operational degradation in mechanical systems, and is indicated by the presence of wear particles smaller than 15 mm in the major dimension. Sliding wear occurs whenever mechanical systems are operated beyond their normal load and/or speed envelope, as we did in our testing; it is indicated by the presence of flat, coarse, striated platelets exceeding 20 mm in their major dimension.

Each of the various paths to failure passed through at least one of three observable alarm conditions (our term for conditions indicating a high risk of imminent failure): cutting wear, laminar wear, or deficient lubrication. Cutting wear, which arises from misalignment or the presence of solid contaminants in the lubricant, is indicated by swarf-like particles 2-5 mm wide and over 100 mm long [2]. Laminar wear results from rolling contact failure of bearing and gears and is indicated by non-striated platelets of various sizes. Deficient lubrication results from poor design or excessive loading or speeding, and is indicated by the presence of black oxide in the lubricating oil.

Figure 3 (next page) includes run number labels along each path segment. In every case of 2X loading black oxides (indicator for insufficient lubrication) appears in the lubricant prior to breakdown.

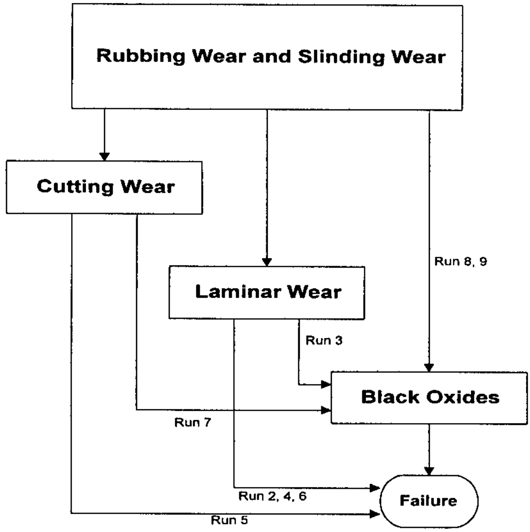

Figure 3. Paths to Failure

All but one case of 3X loading indicators from laminar wear are present; on the other hand only one of these cases showed black oxide observed in the oil sample. While eight samples are hardly enough for valid statistics, these observations suggest that correlating changes in ferrographic content of lubricating oil with operating parameters (e.g. loading level) will facilitate in-line degradation analysis. (As of this writing, oil analysis results for Run #10 have not been finished.) This illustrates the approach on which we are embarking to develop a real-time condition monitoring capability.

Examples of cutting and sliding wear are exhibited in Figures 4 and 5 below, [5].

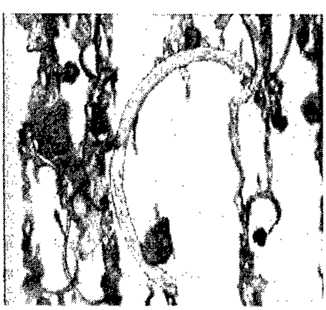

Figure 4. Cutting Wear

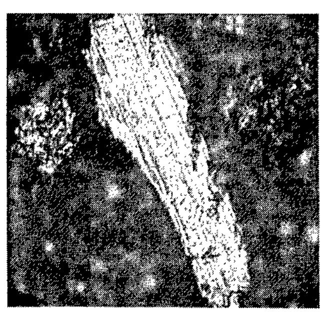

Figure 5. Sliding Wear

Summary & Conclusion: A testbed setup (MDTB) for researching machine component failure detection, diagnosis, and prediction using a medium grade quality off-the-shelf gearbox has been described. Furthermore, wear particle oil lubricant ferrography results as processed by the JOAP have also been presented.

High rdn values (figure of merit) indicated primarily rubbing, sliding, and laminar wear. Cutting wear seemed absent or was not reported in many cases. Oddly, Run #4 had the maximum allowable rdn reading in 3 out of 4 wear categories, but lasted the longest time on load at 146 hrs. Thus, to a large extent correlation between run times in Figure 2 and wear analysis in Table II is somewhat inconclusive. Sampling at the end of each run only yields the final figures of merit for the condition of oil debris contamination, but is not sufficient for tracking or predicting failure along the way. For this we need to sample more often per run.

To accomplish this an on-line dielectric-based oil condition monitor has been installed on the MDTB. Other on-line oil monitoring sensors are also under consideration. In a future paper, we shall report the results and performance of these on-line continuous oil condition sensors as well as their overall predictive diagnostic effectiveness when fusing with other sensor data types such as vibration.

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Particle Transfer from Magnetic Plugs

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Abstract: Magnetic drain plugs have been in use for over thirty years and have developed from simple magnets to self indicating devices. The purpose of this paper is to review the debris transfer from the magnetic plug and suggest procedures to reduce the operator effort, increase the efficiency of the debris transfer and to improve measurement repeatability. Three new procedures are also proposed for review : the fitting of a plastic or metallic sheath, neutralisation of the magnetic attraction and the use of wax to remove the debris.

Keywords: Condition monitoring; magnetic drain plugs; wear debris analysis.

Introduction: Magnetic plugs have been in use for over thirty years and have developed from simple magnets to self indicating devices e.g. QDM - Quantitative Debris Monitor [1]. In many current applications, both civil and military, a standard magnetic plug which has to be removed from the system for visual inspection is still utilised and the method of particle transfer from the plug has basically remained unchanged : an initial solvent cleaning process followed by an application of sellotape (Figure 1). Optical microscopy and X-Ray Fluorescence have enhanced particle recognition by determining the material composition of the collected debris. The advent of computer imaging analysis, numerical and neural network analysis are currently generating expert systems to automatically classify the wear debris generated during the wear process.[2].

It is the purpose of this paper to review the transfer procedures of the attached debris from the magnetic plug and suggest modifications to reduce the operator effort, increase the efficiency of the debris extraction and to improve measurement repeatability. Three new techniques are also proposed for review : the fitting of a plastic or metallic sheath, neutralisation of the magnetic attraction and the use of wax to remove the debris.

Standard Sellotape Method: This method requires an initial cleaning of the magnetic plug by a suitable solvent. The advent of the 'Montreal Protocol' for solvents and its

implementation have created difficulties due to the absence of an equally efficient alternative to the chlorinated hydrocarbons. Alternatives have

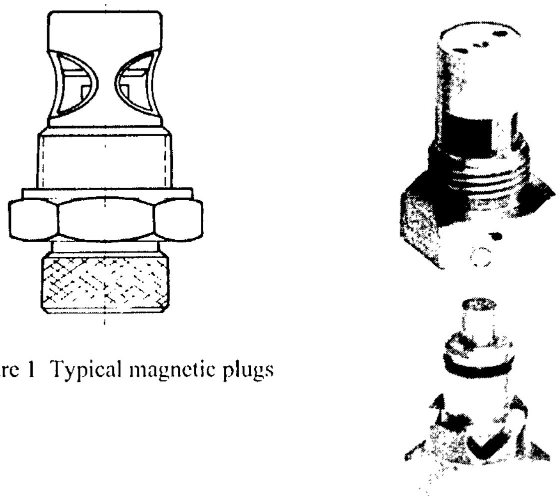

Figure 1 Typical magnetic plugs

however been proposed and accepted by the TSC of JOAP, Pensacola [3]. After removal of all traces of the lubricant or hydraulic fluid from the face of the magnetic plug a strip of sellotape is pressed against the plug face and peeled away with the wear debris and contaminants attached to the adhesive face of the sellotape. At this stage the tape is attached to a record card and may then be placed on a sensor which measures the ferrous content. This stage has posed numerous problems to the operator due to the position sensitivity of the ferrous debris on the sensor. The following procedure is proposed which overcomes this problem.

This procedure suggests the use of a light box' similar to the box used for viewing photographic slides.

Once the debris has been 'wiped' from the magnetic plug using sellotape, the strip with the attached debris may be positioned on the record card in the appropriate centralised position aided by the back-lighting from the light box. The debris is clearly visible in a centralised position and will obviate the presence of operator sensitivity and ensure a more consistent measurement when utilising a 'Wear Debris Tester instrument.' [4]

An alternative method which has shown superior sensitivity, more consistent and hence repeatable results is the use of an adapter with the Ferrous Debris Monitor (Particle Quantifier)[5]. The sellotape strip, with the extracted debris attached, as described above, is pressed on to the adapter shown in Figure 2. The debris is centred within the annulus using the light box method. The adapter is then placed on the Ferrous Debris Monitor for

measurement of the ferrous debris content with no further preparation (Figure 3). Repeated tests and rotation of the adapter have shown repeatability of better than 3 per cent for the PQ Index.

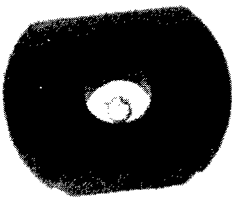

Figure 2 Adaptor for debris measurement

Figure 3 Ferrous Debris Monitor (PQP)

Subsequent microscope examination of the debris is facilitated by the debris being attached to the adhesive side of the sellotape. Auto focusing of the optical microscope is maintained and viewing of the debris does not therefore have to be carried out through the sellotape, a procedure which distorts the image. Use of Mylar tape instead of the standard sellotape enables the particles to be prepared for electron microscope examination and XRF analysis without further treatment.

Reduction of Magnetic Attraction: Particles on the magnetic plug are often distributed around the flank of the plug as well as on the face of the plug. In order to remove these particles the sellotape has to be wrapped around the flank. The attached debris often results in an uneven particle distribution.

A device has been developed to both scrape the flank of the plug and at the same time reduce the magnetic attractive force at the plug face. This device is illustrated in the Figure 4.

The steps to remove the particles are simple. Firstly, the magnetic plug is located on a spring loaded seat, the 'jaws' of the clamp are then closed leaving the plug face proud of the clamp by several millimetres. Surrounding the plug with soft iron effectively reduces the magnetic field - a reduction in excess of 80 per cent is achieved. A sellotape strip is placed over the protruding plug end face and with pressure from the thumb the plug is pressed down on the spring loaded seat such that the plug flanks are scraped clean and all these particles together with the particles attached to the plug face are attached by the

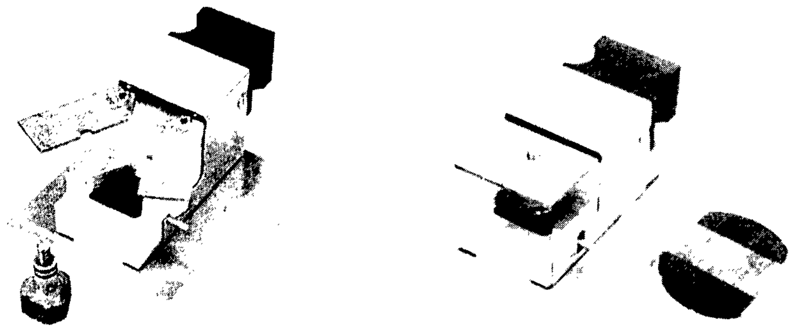

Figure 4 Device for the reduction of magnetic attraction and particle removal

adhesive of the sellotape. The reduction of the magnetic field enables all the particles to be more effectively removed and concentrated in a circular region. The use of a soft rubber stopper has been found to be more effective than pressing with a finger or thumb ensuring removal of all the debris. The sellotape with the particles attached may then be positioned centrally on the adapter and measured using the PQ analyser. The field strength of the magnetic plug, when removed from this device, returns to its original strength.

Sleeve Technique: Most of the magnetic plugs in use have a cylindrical shape and are over one centimetre long. The plug fitting is a self sealing device such that when the plug is either fitted or removed, the housing self seals so that no fluid is allowed to escape. The housing allows the plug face to be positioned directly in the fluid stream or at an elbow located in the fluid circuit.

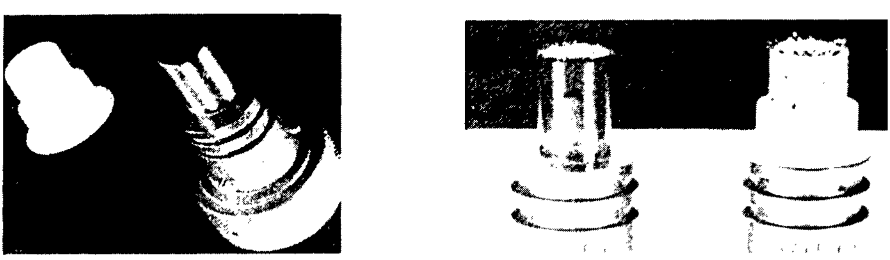

Figure 5 Magnetic plug sleeves

To facilitate the removal of particles from the plug a sleeve may be fitted as shown in Figure 5 [6]. The plug material may be either non magnetic plastic or mild steel. A mild

steel sleeve has however, been found to be more effective. The mild steel sleeve maintains a low level of magnetic attraction when removed from the magnetic plug. A slight tap of the sleeve is then sufficient to remove all the particles which may then be collected in a small plastic cup. The PQ analyser then measures the ferrous content of the particles.

Tedeco, the manufacturers of magnetic plugs, have also developed a sleeve adaptation to their standard fitting. Figure 6 illustrates their design [7]

A withdrawable magnet is located inside the plug housing. This housing with its magnet is released from the gearbox in the normal way using the bayonet fitting. The housing is then positioned over a collector fixture and the magnet removed from the housing. The debris is attracted to the collector fixture by the transfer magnetic.

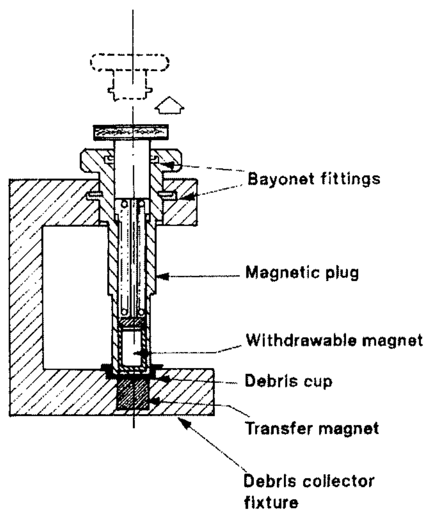

Figure 6 Tedeco sleeve adaptor

Particle Presentation: One of the problems with optical and electron microscopic examination of wear particles collected from a magnetic plug is the overlapping of the particles. Computerised image analysis of these overlapping particles results in erroneous data. This problem may be overcome by placing the plastic cup containing the particles removed from the plug on a rubber magnetic pad. Gentle sliding motion of the cup over

the pad rearranges the particles in rows more suitable for microscopic examination (see Figure 7).

A further advantage of this method is that the particles are unlikely to be altered by pressure as would be the case when pressure is applied to the sellotape to effect the adhesion between tape and particle.

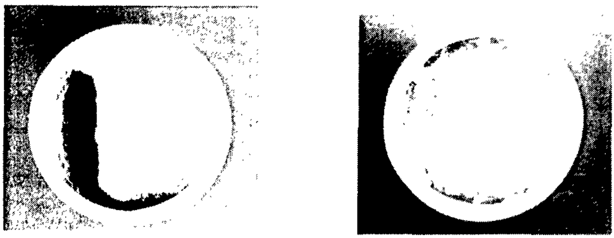

Figure 7 Particle separation using a rubber magnetic pad

Wax Method [8]: A further adaptation of the sleeve technique is the use of wax to surround the plug after its removal from the housing.

Upon the removal of the magnetic plug, the end which has the debris attached is dipped into molten wax and repeatedly dipped three or four times until a coating is formed in a similar way to the formation of a wax candle. The wax bath would have been heated and maintained at approximately 60 degrees C. The wax used in this evaluation was standard paraffin wax although it may be substituted for other waxes, resins or gels which are used in model or investment casting.

The solid wax surrounding the magnetic plug may be slid along the plug until the capsule is free of the plug. Removal of the wax is facilitated if the plug, after removal from the housing, has not been cleaned with solvent. The oil retained on the surface of the plug acts as a release agent. The wax capsule within which the debris from the plug is embedded may then be accurately centred above the measuring head of the Ferrous Debris Monitor (PQ). This procedure avoids the operator optimising the debris position on the measuring instrument.

If the debris has to be viewed by either optical or electron microscope it may be separated from the wax by adding a small quantity of petroleum spirit in a suitable container. Agitation of the container facilitates the dissolution of the wax. A magnet held outside the container allows the solution to be decanted leaving the particles free to be viewed. If a

gel or resin had been used then the appropriate solvent would be used. This may in some cases be water.

Conclusions: A number of methods for the removal of debris from magnetic drain plugs has been presented. These methods are at present being tested in the field and it is the field operators who will judge the efficacy of debris removal and examination by these methods..

Acknowledgements: The help of colleagues at Swansea Tribology Services, the Department of Mechanical Engineering and Steve Greenfield of Vickers (Tedeco) Ltd is gratefully acknowledged.

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New Dimensions in Oil Debris Analysis - the Automated, Real Time, On Line Analysis of Debris Particle Shape

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Abstract: Analysis of debris particles in machinery lubricating oil has long been used to detect the onset of wear and failure of oil wetted components in machinery. This paper explores the potential for direct linkage between on line particle shape detection and the automated early detection of machinery failures.

The development and application of an optimum set of feature vectors based upon extensive particle shape data bases is designed to allow automation of the shape detection process, separation of fault and non-fault related debris, tracking of specific fault types, the elimination of false calls from non-failure related debris, and the ability to provide direct fault specific corroboration of machinery faults to vibration based analysis systems, such as HUMS.

The paper contrasts this capability with current on line and off line particle detection and classification practice and capability.

Finally the paper briefly describes LaserNet Fines On Line, a new technology embodying this capability designed to detect and classify metallic and non metallic particles sized from 5 microns to greater than 1000 microns.

Key Words: Condition Monitoring, Oil Debris, Particle Shape, Wear, Fatigue, Detection, Lubrication System, Lubricant, Optical, Scanning.

Introduction: Shrinking Military Operation and Maintenance budgets are dictating a change in the approach to maintaining our military fleets and especially the machinery content of our weapon systems. The addition of new mission requirements and increased readiness, coupled with the shrinking budget scenario have dictated a change from traditional time based maintenance to Condition Based Maintenance (CBM). Effective CBM relies on reliable automated diagnostics with minimum (or no) false alarms.

Traditional diagnostic methods, that require human experts for data interpretation represent weak points in the transition to CBM and appear to be likely targets for change.

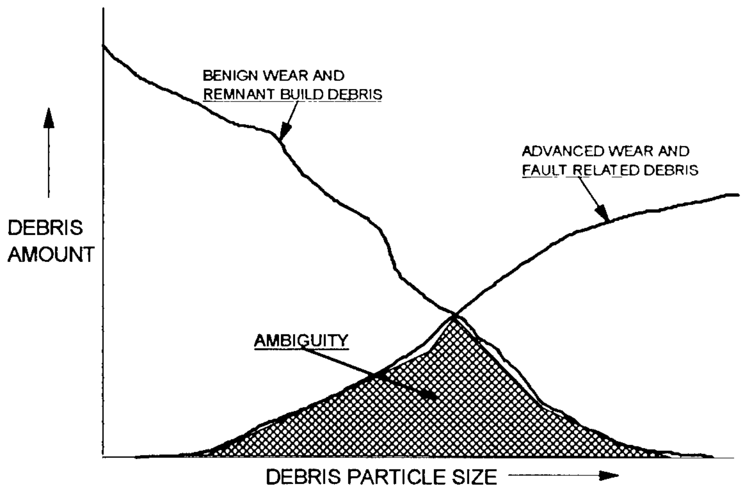
Analysis of the oil borne debris in machinery lubrication systems has long been recognized as an important and direct indicator of the wear state of oil wetted components such as gears and bearings. Laboratory methods have been developed and widely applied to analyze small debris in oil samples for elemental content as an indicator of wear state in machinery. Analysis of larger debris from magnetic plugs placed in machinery lubrication systems oil flow has allowed the trained observer to determine debris size, shape, visual appearance, and to judge machine condition based on prior experience. The move to CBM and the forward deployed posture of weapons platforms has caused some reconsideration of the reliance on laboratory analysis of debris data, and renewed the trend toward increased reliance on real time on board oil debris analysis.

A Perspective on The Problem: The standard for on board oil debris detection has been the magnetic plug and its automated counterpart, the electric chip detector. These have served as "last resort" emergency situation indicators for more than 40 years while particle sensor after particle sensor has tried to replace them. While electric chip detectors do warn of catastrophic failure, they also have an unsatisfactory false alarm tendency. Magnetic plug debris analysis by trained experts remains the most successful early failure detector in use today. The main drawback to this technology is the dependence upon extensive human expert analysis capability and experience. On board oil debris particle detection systems would seem to offer the best solution to this problem, if it weren't for the problems presented by current technology systems of that type.

The current state of the art of advanced on board oil debris particle detection technology has inhibited fielding advanced capability on board systems for nearly a decade. Most current technology systems sense particle size only and some sense ferrous as well as larger sizes of non ferrous particles. These sensors are based on electrostatic, magnetic or electromagnetic sensing technology. Most of these systems appear to operate well on the bench and on oil flow system or gear box test stands. Some operate fairly well on turbine engines in a test stand scenario. Usually they will easily pass Mil Specification EMI and Vibration tests. Aircraft, especially helicopters, however, tend to have EMI and vibration environments that can easily be 10 to 30 times greater than the Mil Specification levels. In these environments current electromagnetic sensing technology usually falters as evidenced by high false alarm rates. The solution most often applied is to decrease the sensor sensitivity until false alarms diminish and then accept the larger particle detection threshold that results. The willingness of the user community to accept this solution is evidenced by the number of on board particle counting systems of this type in production today -- none.

Even if these particle size sensors can be made to work, their ability to give early warning of impending failure or to corroborate vibration detection of wear based faults will be diminished by their inability to separate fault and non-fault related debris based solely on size measurement . Many machines generate benign debris and flush out build

debris periodically during operation. Figure 1. depicts a typical machinery debris generation pattern, where non-failure related debris size ranges can overlap failure related debris size ranges. Since debris detectors must operate ahead of the lubrication system filter, there is little or no effect of fine filtration on this problem. Debris detectors that rely on size detection only could be limited to the upper size bound of non-failure related debris before an accurate measure of failure related debris can be obtained. Small debris detection in the micron range presents no advantage unless the detector can distinguish between benign "polishing" and pre fault wear which is generally believed to occur above 10 microns.. This presents still another false alarm mode for current " size only " detection technologies.

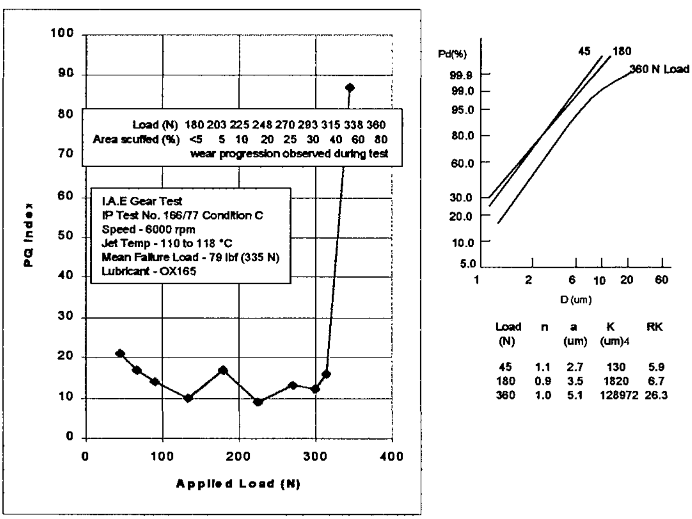


TYPICAL DEBRIS SIZE VS. AMOUNT CURVES
FIGURE 1

Alternative Technologies: There continue to be attempts to transition successful Laboratory proven technologies into on line sensors. Significant improvements in CBM capability can often be achieved even if these techniques can only be transferred to shipboard or plane side systems, where logistic benefits including reduced analysis times can be achieved. Technologies such as FTIR and XRF while still requiring sample preparation and expert analysis might provide some logistic benefits if the application penalties (like complicated debris separation and particle segregation of debris trapped in oil filters and subsequent sample preparation and handling) don't outweigh the benefits. Successful on board debris detection and analysis, however, apparently requires application of more robust and less expert dependent technology.

The U. S. Naval Research Laboratory, in cooperation with the U.K. NAML and The University of Wales, Swansea, has developed and fielded a family of optical debris sensors, called LaserNet, based on detection and classification of debris size and shape. These detectors operate with microsecond duration pulsed lasers, analyze optical images of debris and therefore won't respond to the harsh vibration and EMI environments that affect electromagnetic or electrostatic type debris sensors. Debris particle size detection is the easier part of the detection and classification process. The shape classification process is the heart of this technology. This feature provides the ability to separate out non fault related debris by shape regardless of size, determine what failure mechanism or mechanisms are occurring, and the severity of each mechanism. In reality, this is an automation of a major part of the visual debris analysis techniques successfully applied for the past 2 decades.

Debris Size and Shape as Analysis Tools : Size distributions are useful in confirming the type of wear and also when a transition has occurred (15,16). To first observe the particles and then determine the size distribution, involves the use of computer - aided, image processing and analysis procedures (17). The manner in which particle size distribution is utilised is illustrated in Figure 2 which shows some results obtained from a gear test in which scuffing failure occurred.



Load (N)	n	a (um)	K (um)4	RK
45	1.1	2.7	130	5.9
180	0.9	3.5	1820	6.7
360	1.0	5.1	128972	26.3

Figure 2 Scuffing Wear Progression with Load - I.A.E. Gear Machine Test - Wear Particle concentration, Size Distribution and Morphology

Commencing the test with a new pair of gears fitted, the early run-in wear at light load was followed by a period of mild wear in the middle load range, in which the debris was mainly rubbing wear, The size distributions are linear, although the slope and scale parameters for the running- in wear stage differ from those in the middle load range. At higher load, where scuffing behaviour is encountered, the size distribution becomes non-linear. This is indicative of a small number of larger size, (20 - 30,um) severe sliding wear particles associated with an acute scuffing mode of wear. It was also observed visually that the particle shape changed as wear progressed from rubbing to scuffing and later to severe sliding.

The morphology of particles is the most problematical of analyses to perform and yet, potentially, yields the most information in regard to the diagnosis of the wear mode and its underlying mechanism. The morphologies and associated terminology of the ferrography wear atlas (13), have been adopted almost universally by those engaged in wear debris analysis for monitoring the condition of machinery. The tribology research community have not so far reached the same degree of unanimity in describing wear particles collected under controlled laboratory wear tests (4). This is perhaps to be expected given the extensive variety of situations under investigation and the problem is exacerbated by the proliferation of sampling and processing devices and techniques employed to prepare samples for analysis. Attempts to make the analysis, and subsequent interpretation of the findings, more systematic have been reported (18) which has involved the use of computerised procedures (19,20). Computer-aided procedures are also enlisted to perform particle recognition (21). This also seeks to exploit HyperText Markup Language (HTML) methods, which can be operated through browser systems such as *Netscape, Navigator* or *Mosaic* connected to the World-Wide Web (WWW). What has emerged from the more recent developments is that, whereas a universal atlas, coupled to a coding system for identifying particle types and the associated severity of wear, is useful for general particle diagnosis (22), it is necessary to set up 'machine - specific' methods (23). It is also advantageous to be able to transmit images directly from one location to another so that other 'expert' analysists can perform an independent diagnosis.

The quantification of morphological attributes has implications which go far beyond wear particulate. Nevertheless, a number of developments have been reported in the literature which correlate quantitative shape parameters with wear phenomena. The principal attributes involved are: outline shape and edge detail, thickness, surface texture and colour (composition). Size is also implicated but this has been discussed above.

Morphological descriptors are specified in terms of outline shape, edge detail, and thickness. Distinguishing surface features, such as striations, holes and cracks, etc., are also identified. Details of the associated mathematical expressions used to define the terms quantitatively are presented elsewhere, (24,25). In terms of general shape features, form factors, such as *Aspect Ratio* or *Roundness Factor,* are used to describe the outline shape (26). A more precise determination is obtained by utilising Fourier analysis techniques,

(27,28). Edge detail is determined by utilising curvature analysis (29). Fractal analysis techniques have also been utilised to distinguish particles generated under different wear conditions, (25,30,31). Particle thickness is not easily determined in optical microscope systems; scanning electron or confocall microscopes, therefore, must be utilised, (32). Surface features are identified using fractals (31) and neural network methods (33). For all of these methods, computer - based procedures are utilised in order to achieve the desired result within an acceptable timescale.

Figure 3. tabulates the results of a computer based shape analysis of particles generated from a wear test conducted on a laboratory developed slipping assembly. Roundness and edge detail (as illustrated by its Kurtosis) are tabulated for the wear conditions encountered.

Shape Analysis				
Wear Mechanism	Size (um)	Aspect Ratio	Roundness Factor	Edge Detail (Kurtosis)
Mild Abrasive	< 10 um	> 2.0	> 2.5	> 4.0
Severe Abrasive	> 15 um	> 2.0	> 2.5	> 4.0
Adhesive-Abrasive	> 15 um	< 2.0	< 3.0	< 4.5

Figure 3
Computer - based analysis of wear debris
from Laboratory slipping system development

While LaserNet applies only a portion of the potentially available data resulting from a complete analysis of debris particles, it achieves a level of automation of the analysis not previously available and can be augmented, where time permits, by the additional analytical approaches outlined above.

New Applications of LaserNet Technology: Presently, LaserNet employs a number of particle shape classifiers correlated with machinery wear modes. These Include:

Aspect Ratio: The ratio of particle image area divided be maximum linear dimension squared.

Circularity : The ratio of the square of the perimeter (length of the object boundary) divided by 4 Pi times the area.

Perimeter : Length of the object boundary.

The Naval Research Laboratory / University of Wales co-operative Program is continuing to develop and incorporate advanced particle wear shape indicators to enhance LaserNet performance on additional types of machinery and fluids.

LaserNet Fines On Line System : The LaserNet full flow Oil Debris Monitor has been developed, bench tested and evaluated on a T-700 engine at the NAWC Power Train Test Center in Trenton, NJ. The results, previously reported, indicate an ability to detect and classify debris type and to achieve a 0 % False Alarm Rate. LaserNet Fines Bench Sample Analysis technology has been transferred to industry and production prototypes produced for shore based laboratory and shipboard testing.

The LaserNet technology development thrust is now focused on the development of a modular on line version of the LaserNet Fines capable of integration with the LaserNet Full Flow System (or other on line system) or stand alone operation.

As currently configured, this unit will continuously extract a small sample from the scavenge oil pump output flow and analyse the debris size and shape to determine the onset of early wear, or the existence of particulate contamination. An active, driven rotary sample generator wipes a fresh 100 um thick sample oil film across an imaging surface and analysis of the sample can be performed at up to 100 frames per second. The design of the rotary sample generator provides a slight pressure increase to the oil and allows the sampled oil to be re-injected into the scavenge line oil flow. A prototype of the system has been assembled and is now being tested at NRL. This system can be applied to a wide variety of flowing and splash lubricated machinery as well as other fluids (such as hydraulic) to detect wear and contamination early in the failure process. The unit will detect debris in the < 5 um to 100 um size range and, when combined with LaserNet Full Flow, will detect the full < 5 um to > 1000 um wear and failure debris size range and thus becoming an enabling technology for Machinery Health Prognosis and CBM.

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Intelligent Debris Analyzer
A New Tool For Monitoring Lubrication Machines

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Abstract: Critical aircraft and marine components such as turbine engines and gear boxes usually require health monitoring techniques to periodically assess their condition. Debris entrapped in their oil filters contains a vast amount of untapped information. If interpreted properly, this information can be interpreted and applied for monitoring the overall machine condition and can be used to make important and relevant maintenance recommendations. Standard oil analysis methods do not generate the results required to make similar recommendations for the operation of systems with fine filtration units. Furthermore, current manual methods for filter debris analysis rely on expert knowledge and expertise and are time-consuming, expensive and inconsistent. They are, therefore, not really exportable from the laboratory to the shop floor. This paper describes a novel Intelligent Debris Analyzer (IDA) system for detection of impending failures and diagnosis of wear trending. IDA is a hybrid artificial intelligence system incorporating digital image processing, pattern recognition and an expert system. This new system automatically evaluates the debris image, draws an expert conclusion on wear conditions and recommends maintenance actions.

Key Words: Filter debris analysis, image processing, pattern recognition, expert system, artificial intelligence and machine condition assessment.

Background: Traditional methods of determining wear condition of oil-wetted machinery include the use of oil pressure and temperature indicators, magnetic electric chip detectors, optical particle counters, spectrometric oil analysis (SOA) and ferrography. These approaches are very successful in predicting failures when a number of specific criteria are met:

- The small debris particle size for which spectrometric oil methods are sensitive is indicative of the total debris generated by the equipment.
- The debris left in the filtered oil is sufficient to be useful diagnostically.
- The total amount of debris generated is indicative of the machinery condition.

In the past, when coarse filtration systems were used, all of these conditions were met. In today's fine filtration systems (less than 10 microns), most of the large particles with

one or more of the above criteria are not met since all debris greater than the pore size of the filter is trapped. Consequently, both ferrography and SOA are deemed unusable for determining the wear condition of these systems. Furthermore, certain types of failures, such as gear failures, will produce particles too large to be detected by most conventional methods. In addition, a significant amount of experimental data on operating systems suggests that the amount of debris being generated is not the sole indication of wear condition, and that size, and, to a lesser degree, conformation of the particles is as important as quantity.

Introduction: This research and development project was based on work that took place at the Canadian Defence Research Establishment Pacific in the early 1990's. The approach used image analysis techniques combined with innovative artificial intelligence methods to lead to an automated monitoring technology. The project included four basic areas of research: Post-cleaning Debris Separation, Digitization Technology, Imaging and Interpretation using Pattern Recognition, and Neural Networks Methods.

With this condition monitoring technique, it is the assessment of information contained in the filter that is important. To remove the debris in the filter, an ultrasonic cleaning bath in a varsol solution was used. Once the debris was removed, which usually took around thirty minutes, the varsol solution contained most of the debris that had been captured by the filter. To assist in the evaluation process, magnetic segregation was performed prior to imaging the results. The system performed analysis as per the logical diagram shown in Figure 1.

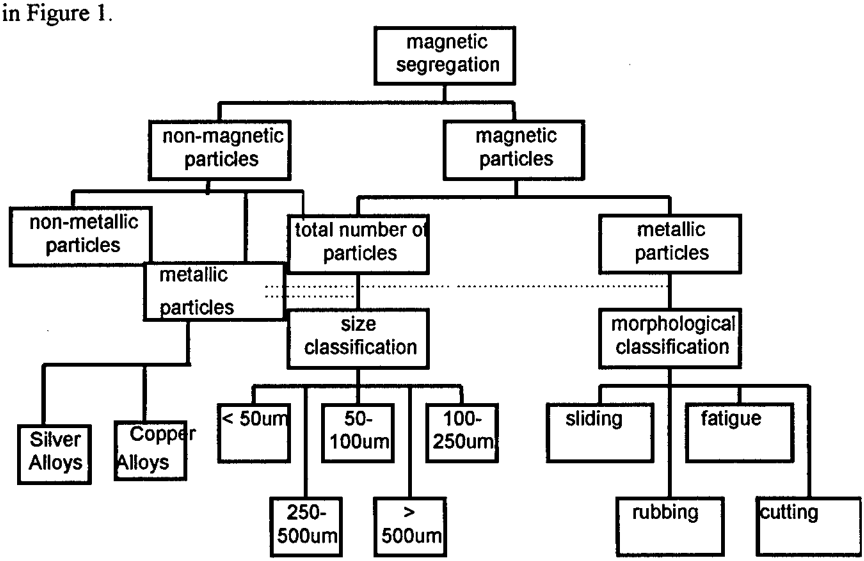

Figure 1. IDA Logic Decision Tree

As shown in Figure 1, considerable information was extracted from the system. This information included particle size distributions, % area covered, wear classes and trend.

All of this information was available for both the magnetic and non-magnetic particles through digitizing, imaging and interpreting the filter debris. The IDA platform used to perform this analysis consisted of a metallurgical microscope, a XY-motorized stage and controller, optical lenses, a color camera, a personal computer and a graphic frame grabber. A schematic representation of the digitizing platform is shown in Figure 2.

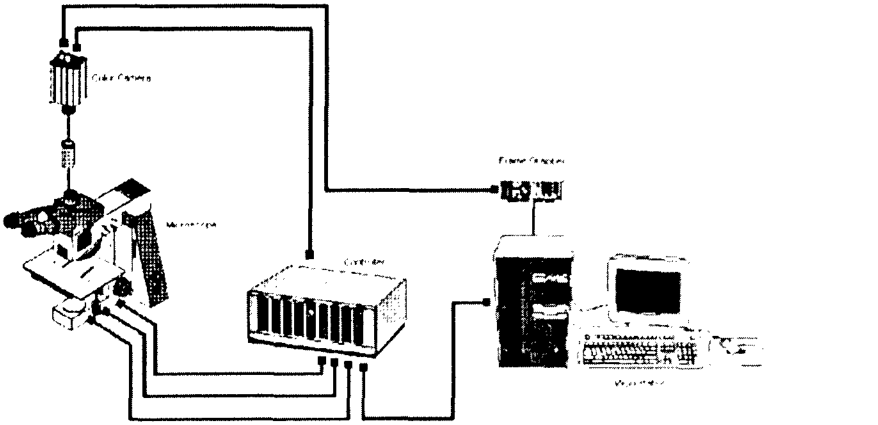

Figure 2. The IDA Platform

Description: The imaging process began by stitching images together to obtain a "mosaic" image. Adaptive software adjustment of the contrast and colour characteristics of the captured images was performed to ensure matching of adjacent images. The process of image scanning and stitching is illustrated in Figure 3.

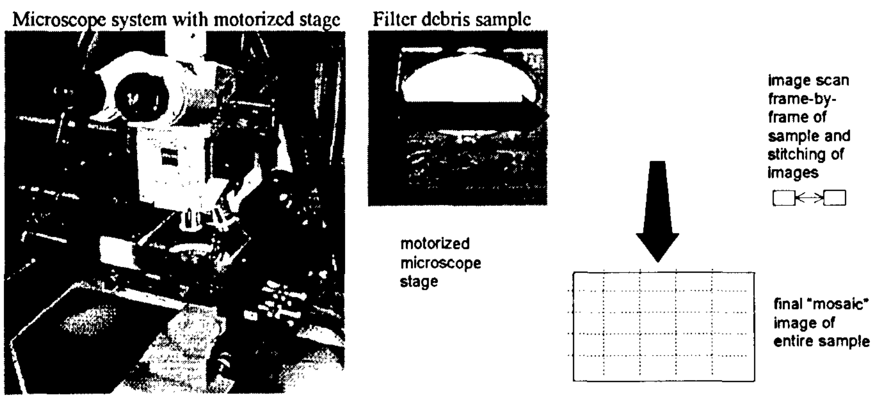

Figure 3- The Mosaic Image

Once an image mosaic was obtained, the particles in the image were segmented for particle identification. To perform this task, an edge-detection filter and auto-thresholding algorithm were developed and incorporated. Figure 4 shows the results of the segmentation on typical metallic debris.

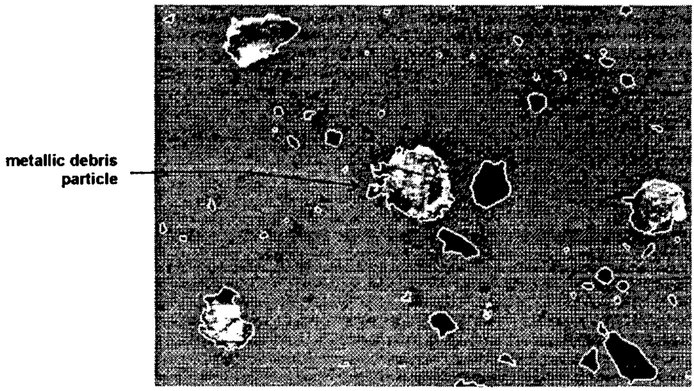

Figure 4. Debris Segmentation

With the objects properly segmented, labeling routines were called into operation to aid in the analysis of the detected objects. Functions were used to classify the detected object by class size. To enhance the quality of the mosaic image, auto-focus, zoom and color characteristics were included. A number of digital filters were applied: lowpass, auto-threshold, sobel edge detecting, binary, thinning, and morphological closing filters. Each particle was segmented from the filter patch background and saved as an individual image file. Then, the particle image was fitted to an ellipse and the size of the particle was extracted by calculating the major axis of its associated ellipse. Particle size classification and nümber counting were processed automatically for both the metallic and non-metallic particles. As well as using thresholding techniques, trending was used to recommend a maintenance action.

The system provided an evaluation of the machine condition anomalies and its severity based on size distribution counts and trends. In addition, a morphological assessment of the debris was also included. Using pattern recognition techniques and the morphological features, each particle was segregated by its wear type. In addition, texture features and color features were weighted to distinguish between metallic particles and non metallic particles. A database, embedded into the system, stores the classification results. The overall result was a system that provided a quantitative assessment of the extent and type of debris by classifying debris as cutting, fatigue, sliding and rubbing wear. The wear type condition was used to provide additional recommended maintenance actions. To obtain this assessment, a number of spatial and frequency-based features were extracted from the debris images. Pattern recognition and neural networks were used to develop a

classifier. From expert knowledge, a set of deterministic rules adapted to specific components was used to identify the cause of an abnormal problem.

The current result can easily be saved or retrieved via the database engine to perform trending analysis. The expert knowledge was collected from lubrication engineers and delivered to the expert system at the very onset of the consultation session. The forward chaining algorithm, serving as a reference engine, analyzed the classification and trending results. It provided additional tools to the system to diagnose wear condition and provide maintenance recommendations. The process is shown schematically in Figure 5.

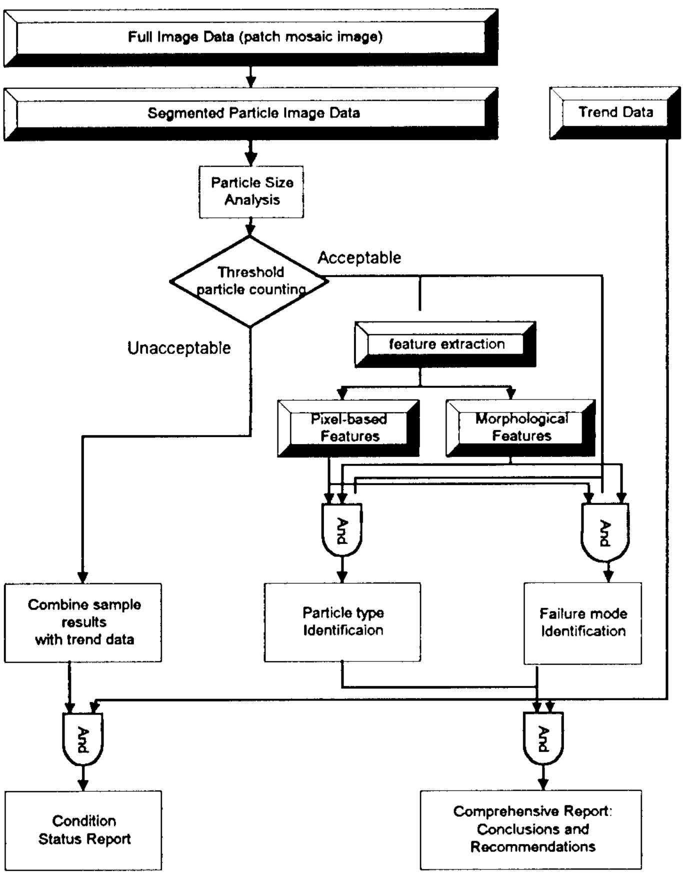

Figure 5- IDA Decision Process

Conclusion. An image analysis workstation has been developed and incorporated into an automated system for diagnosing and tracking the condition of oil-wetted machinery. The acquisition system includes a metallurgical microscope, a servo motor stage and its controller, a digital camera, an image grabber board and a PC computer. Digital image processing techniques automatically enhance, segment and count debris particles contained in oil filters. Debris is classified using morphological features into diagnostic categories such as rubbing, cutting, fatigue and sliding wear. A database embedded into the system performs trending analysis. A deterministic expert system used as a reference engine, analyzes the classification and trending results.

IDA is a powerful monitoring technique that offers a new means to diagnose wear condition and provide maintenance recommendations for components of oil-wetted machinery. It has the capability of being used with both standard and fine-filtration systems and will be available commercially in the near future.

Fourier Transform Infrared Analysis Applied to Maintenance Management - Making the Most of this Powerful Tool

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Abstract: The utility of infrared analysis for industrial applications has increased due to the availability of Fourier transform infrared (FT-IR) spectrometers. This increase has come about because of the advantages that FT-IR offers over other types of infrared equipment. These advantages include speed of analysis, good wavelength stability, high-energy throughput, and high sensitivity. The above factors coupled with PC control, easy-to-use software; small footprint and relatively low purchase cost have made modern FT-IR systems a more powerful and cost-effective analytical tool. Application of this tool to maintenance management is reaching new heights because of the many facets of maintenance quality assurance to which infrared analysis can be applied. It is through a better understanding of the capabilities of FT-IR analysis to solve maintenance management problems that its use will continue to grow.

Key Words: Condition monitoring; Fourier transform infrared spectroscopy; FT-IR; incoming material identification; lubricant analysis; power generation; quality control.

Introduction: In modern proactive maintenance management, the goal is to provide maximum uptime and proper operation of mechanical devices. This is needed to assure that the work done by a piece of mechanical equipment is done with the greatest possible safety and reliability. In support of maintenance management efforts, several diagnostic techniques are applied to provide information that can be used to assess the performance of equipment. These techniques include such things as vibration analysis and lubricant analysis.

The use of these diagnostic tools is justified by the predictive capabilities they provide. The information from diagnostic tests can be used in the prevention of catastrophic failures and scheduling of maintenance activities. However, many times the economic justification for completing analysis associated with equipment maintenance is difficult to assess. The value of a particular technique used in maintenance management is measured not only by the cost of purchasing the equipment, but also by the cost and quality of information associated with using the tool. Also important is the ease with which useful information is obtained. One diagnostic tool that has been finding increased use in maintenance management is Fourier transform infrared (FT-IR) spectroscopy.

The increase in use of FT-IR instrumentation has evolved for several reasons related to the technological advancement of the technique. The advancement in the utility of FT-IR spectroscopy for routine quality control and process analysis has occurred because of the advantages of FT-IR compared to other infrared techniques. These advantages include high sensitivity, high-energy throughput, high resolution, and good wavelength stability. However, the expansion of the technique into routine analysis areas has only occurred within the last fifteen years. This expansion has occurred due to four basic reasons: the rapid advancement in high powered PC computers, decrease in instrument size, lowering of prices, and the development of easy to use software.

Two application areas in maintenance management where FT-IR spectroscopy can be used include verification of incoming material and lubricant condition monitoring. The utility of FT-IR instrumentation in completing both of these functions provides greater value and justification for the purchase of the equipment. It also provides a method that can be applied in a total quality management for fluids and non-metallic solid materials.

Many problems occur as a result of incorrect materials being applied in maintenance practices. FT-IR is an excellent tool for identification of non-metallic incoming materials of all types, including gaskets, o-rings, greases, oils and other fluids. In the nuclear power industry, gaskets and o-rings must be certified before they are stocked for use in maintenance. FT-IR is quick, easy, and most times non-destructive, and it provides positive identification of many non-metallic materials. Because of these facts, FT-IR is one if the best tools available for a variety of identification and quality verification purposes. This is because of the availability of a variety of sampling devices that allow the FT-IR to be used in ways that provide molecular structure information quickly and easily. Application to the identification and verification of lubricants and other fluids is a sound practice in a well-controlled lubricant condition-monitoring program.

The application of infrared analysis to used lubricant condition monitoring has grown tremendously in the last ten years. The speed of analysis makes FT-IR an attractive option for the rapid screening of used lubricants for oxidation breakdown

products and contaminants, such as water, fuel, antifreeze, fuel, and soot. This can shorten laboratory turnaround times and decrease the number of time-consuming traditional oil quality tests that need to be completed. The growth in the use of infrared analysis has been fostered by a general increase in the importance of used lubricant condition monitoring for large industrial and transportation equipment. It provides a way to assure safe operation, prevent catastrophic failures, as well as increase lubricant drain intervals.

This presentation will provide an overview of the approaches currently in use for applying FT-IR analysis to maintenance management. Included will be a discussion of various methods of sample analysis and data treatment schemes, as well as how the FT-IR can be set up to allow non-chemist operators to use it successfully. Particular focus will be on its application in the nuclear power industry. Case studies with cost savings data will be provided.

Principles of Infrared Spectroscopy: Infrared spectroscopy in the mid-infrared region (2.5 to 25 micrometers or 4000 to 400 wavenumber) has been traditionally used to obtain information about the structural composition of molecules. It is particularly useful for identifying structural features and functional groups in organic molecules, but can also be used for the analysis of inorganic molecules, particularly those containing oxygen or nitrogen. The technique is sensitive to atomic combinations where there is a change in dipole moment. This means that hydrocarbons and molecules with combinations of dissimilar atoms are detected. Thus, gases such as carbon monoxide (CO) or nitrous oxide (NO) are readily detected using infrared measurement. Infrared spectra are not obtained from diatomic molecules that are symmetrical, such as nitrogen (N2) or oxygen (O2).

Metal ions are not detected by infrared so that infrared is not useful for wear metal analysis. However, because of the different information obtained, atomic absorption (AA) and atomic emission (AE) spectroscopy are complementary techniques to infrared. For example, zinc in the commonly used additive zinc dithiodiphosphate can be measured directly using AA. The phosphorous-oxygen bond in the phosphate group to which the zinc is bound is detected using infrared. However, tricresol phosphate, another antiwear additive, can only be measured using infrared since it contains no zinc.

Infrared spectroscopy can not only be used to identify materials or components in mixtures; it also can be used to quantify the levels of components in a sample. This fact has led to an expanded role for the technique, especially aided by the introduction and evolution of FT-IR spectrometers.

Modern FT-IR Spectrometers: The advances in FT-IR spectrometers have led to their widespread use for quality control and process monitoring applications. The high sensitivity of FT-IR is brought about by the combination of high-energy throughput and high resolution, which are due to the way the instrument operates. Another feature these instruments have is good wavelength stability because a reference laser is used. These features alone did not lead to a full migration of the technique to quality control and process monitoring applications. The evolution of smaller size, lower cost instruments coupled with high speed, low cost PC computers contributed strongly to the widespread use of the technique that is seen today. Also contributing to the more widespread use has been the development of easy to use software and convenient sampling accessories.

With the advancement of graphical user interfaces, all software on PC computers has become more intuitive to use. FT-IR systems, following this trend, now have software that utilizes these graphical interfaces to allow operators to obtain useful data quickly without having to spend long periods of time learning how to use the software. To further simplify operation, customizable operator interfaces allow a lab manager to set the system up so that only the features needed are seen. Another major advancement that some manufacturers have made is communication between the spectrometer and the computer so that on-board diagnostics are available. These diagnostics allow the operator to quickly determine if problems exist with the system that would prevent them from getting usable data. In addition to these hardware diagnostics, programmable system checks can verify proper operation of the sampling configuration.

Sampling Accessories: The high-energy throughput feature of FT-IR spectrometers is another major reason that has allowed the technique to gain widespread use. It is because of the high-energy throughput and resulting high signal to noise, that a variety of sampling accessories has been developed. These accessories have created more sampling options, which allow simpler and more optimized system operation. A recently introduced feature in some sampling accessories is the ability to place them into the FT-IR instrument and have them recognized by the spectrometer. The operational parameters are automatically set up and a test scan is run to verify that it is working properly. This means that the operator does not have to remember the parameters, since the system sets them automatically.

Sampling techniques for the FT-IR spectrometer that are of most interest in maintenance management include transmission analysis and horizontal attenuated total reflectance (HATR) analysis. With these approaches, most types of samples that will be encountered can be successfully analyzed.

Transmission analysis can be used for most fluids from very low viscosity to relatively high viscosity. For fluids to analyzed in traditional transmission cells they must be pushed or pulled through a thin space between two windows. The

magnitude of the space is around 100 micrometers, which is approximately the thickness of a human hair. Because of this thin film, the practical limit for the use of flow-through transmission cells is between 300 and 400 centistokes (@40°C).

An alternative method for transmission analysis is by the use of a membrane made of porous polyethylene. In this case, a small measured amount of fluid material is pressed into the surface of the polyethylene and it is analyzed once it has been absorbed into the pours. While this method is not as reproducible as the flow-through transmission cell, it is typically adequate for routine analysis. Membranes that have an effective pathlength of around 100 micrometers need to be used to obtain comparable sensitivity to the 100-micrometer transmission cell. The advantage of the porous membrane over the flow-through cell is that it does not require solvents to clean since the membrane is disposable. This is an important safety advantage.

In practice, flow-through transmission cells or porous polyethylene membrane cells with nominal pathlength of 100 micrometers are used to analyze unused and used oils. The transmission cell technique provides good sensitivity for low level additive and contaminant measurement. For new lubricants or other fluids, a comparison can be made of the lubricant or other fluid to determine if it is similar to previously obtained batches. They can also be checked for the presence of contaminants such as water.

For used lubricant analysis, methods are available for condition monitoring which assess the status of the lubricant and mechanical system. The methods apply either new oil reference subtraction followed by assessment of spectral regions, or direct analysis of spectral regions to obtain information from the sample. Spectral features are used to determine relative levels of lubricant breakdown products, such as carbonyl oxidation, nitro-oxidation, sulfur oxidation, and other base oil breakdown products in the case of certain synthetic lubricants. Contaminants that are assessed include water, antifreeze, fuel, or soot. Additive loss can be determined for certain additives, such a phosphate antiwear/antioxidant additives and phenolic antioxidants.

One problem with diesel engine oils is the high levels of soot that are contained in the oil. If the level exceeds 3-4% by weight of soot, the transmission cell technique using a 100-micrometer pathlength becomes no longer useful. The light infrared light can no longer transmit though the sample, and no useful data can be obtained. In this case, an HATR cell is a reasonable alternative to both trend the soot level and check for breakdown products or contaminants. It must be kept in mind however; that the HATR method has lower sensitivity than the transmission cell and increased scanning times should be used as discussed below.

For grease sample analysis, which is becoming of greater concern in maintenance management, neither the flow-through cell nor the membrane can be used. Greases can not be pumped through cells. When placed on a porous membrane they

separate into oil and soaps constituents, which leads to a significant change in the spectral features. The only way to analyze these by transmission is by the use of thin films between removable windows. This approach is time consuming and some type internal standard approach must be used to account for pathlength variations. A much simpler way to handle grease sample analysis is by using an HATR accessory.

HATR is a sampling method that allows a thin film of sample to be placed on the upper surface of an infrared transparent crystal. The infrared light is transmitted through the crystal and bounces off the sample to obtain a spectrum. However, because the total number of bounces through an HATR element is limited, sensitivity of the measurements with HATR is lower than that of a transmission cell. To overcome this situation, a crystal with the highest number of bounces should be used. In practice, either a 45° ZnSe (10-12 bounce) or a 40° ZnSe element can be used. The number of scans collected should be at least two to four times that of the transmission cell. The HATR cell can be used for very thick or very dark samples that can not be done using the transmission cell. Because of optical effects, spectra from HATR and transmission cells can not be directly compared as regards the peak intensities. Corrections can be made to make the peak intensities more comparable. However, peak locations are the same for HATR and transmission cells.

One other important aspect to maintenance management that has not been discussed thus far is the analysis of non-metallic parts used in mechanical systems. This refers to gaskets, o-rings, and other polymeric parts that must be replaced during maintenance activity. This is of particular interest in the nuclear power industry, where these parts must be certified prior to their use. This is regulated in the nuclear power industry to assure that the specified materials are used during maintenance. Even though it is not regulated in other industrial operations, the practice of obtaining and verifying materials from other sources can provide significant cost savings. The FT-IR spectrometer is one of the best methods for analyzing these materials.

In this case, the materials need to pressed against the surface of a single-bounce HATR cell and scanned to obtain a spectrum. This spectrum is compared to spectra of previously analyzed certified materials to obtain a positive identification. The HATR method is, in most cases, non-destructive. Several different types of single-bounce HATR accessories depending on how hard of materials must be analyzed. The harder the material to be analyzed, the more pressure is required to obtain a useful spectrum. The hardness of the material to be analyzed must be considered when determining which particular accessory is needed.

Case Studies: To help obtain a better feel for the value of the FT-IR technique, several case histories have been compiled. They include examples from the nuclear power industry for incoming lubricant verification, used lubricant condition monitoring, and material analysis.

Incoming lubricant case history: A nuclear plant was in an outage and decided to check the incoming lubricant using the FT-IR while the tanker was still on the premises. The analyst stopped the tanker at the gate, pulled a sample, and took it to the FT-IR. Five minutes later (after running the sample through the FT-IR) the analyst realized the lubricant was contaminated by a substance the tanker had previously hauled. The analyst forced the supplier to buy back the lubricant. The cost savings from the lubricant alone: $5,148.00 (1800 gallons at 2.36 per gallon). This cost saving does not take into account the damage or downtime that could have resulted if the lubricant had been added to the turbine it was headed for.

Incoming lubricant case history: A nuclear plant received a shipment of turbine oil that was added to the make up lube reservoir. The plant did not test the lubricant for two days since the plant was powering up from an outage. An operator decided to test the lubricant. When he analyzed the lubricant using the FT-IR, he confirmed that it was contaminated. The supplier came to the plant and paid to clean up the reservoir, but the plant lost two days of running time and had to purchase power from an alternate source in order to supply its customers. Total dollars lost: approximately 1 million dollars.

Lubricant condition monitoring case history: A nuclear plant was using FT-IR for condition monitoring of a condensate pump. The plant noticed the antioxidant additive was depleting at an accelerated rate. Working with the lubricant supplier, the plant was able to "sweeten" the lubricant by adding an additive package concentrate. The plant then monitored the pump closely to prevent having to complete work on the pump prior to the scheduled outage. This close monitoring took place for three months before the outage began. If the pump had needed to be shut down prior to the scheduled outage, the loss of production and scheduling issues could have cost approximately 1 million dollars per day.

Material certification case history: Based on the regulation in the nuclear power industry, the plant must provide "reasonable assurance" that the material used meets the specification for the application. If the plant does not do this internally, they must obtain "Nuclear Grade" certification from outside sources. This certification can cost five times the cost of the parts from a standard commercial source that they certify internally. Therefore, it is very cost effective to buy materials on the open market, and have them certified in-house. Examples of the cost savings are as follows:

Part Description	One time savings ($)	Total savings ($) life of plant*
Heat Removal Seals	22,629	107,163
Gasket	291	2,334
O-Ring	159	4,308
Filter	875	7,634

* - Life of Plant typically is 20 to 30 years, depending on the type and years in service.

Conclusions: FT-IR spectroscopy is a technique that continues to grow in popularity as more applications are found for its use. The technological advances in spectrometers, computers, software and sampling along with lower purchase costs have and will continue to feed this growth process. For maintenance management, the simplification of FT-IR systems, their software and sampling accessories have made them easier to use to obtain useful information. Their use will continue to grow based on the above factors coupled with more standardized methods for interpretation of the data they generate.

The Utilization of FT-IR for Army Oil Condition Monitoring

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Abstract: This paper discusses the implementation and progress of Fourier transform infrared (FT-IR) spectroscopy in the U.S. Army Oil Analysis Program (AOAP). Improvements in the basic FT-IR method, the addition of new analysis capabilities and the impact FT-IR has made on AOAP are presented—expansion of FT-IR to cover hydraulic fluids (petroleum and phosphate ester fluids), new fuel analysis procedures and new cleaning solvent option. The implementation of FT-IR in the Army enabled the return of previously removed aircraft equipment (ODDS) to the AOAP.

Key Words: Army Oil Analysis Program (AOAP); Condition monitoring; Fourier transform infrared (FT-IR) spectroscopy; oil analysis.

Introduction: In the past, the Army Oil Analysis Program (AOAP) determined the condition of lubricants through qualitative, subjective and antiquated tests. Due to progressive equipment degradation, equipment users and materiel developers determined more precise testing technology was needed, particularly in the area of corrosion detection. This requirement was passed to the Joint Oil Analysis Program Technical Support Center (JOAP-TSC) for evaluation. The JOAP-TSC evaluated FT-IR spectroscopy [1,2,3] as a possible replacement for the old methodology. Test and evaluation studies were conducted [4,5,6,7] and the Army adopted the FT-IR as the appropriate technology to meet advanced physical property test requirements. Since

adoption, the Army has procured and fielded FT-IR systems at 12 Army laboratories worldwide. Partially because of this technology, the U.S. Army Aviation and Missile Command has enrolled all of the aviation fleet in the program. The implementation of FT-IR supports the Chief of Staff of the Army's position to aggressively pursue state-of-the-art diagnostics.

Improvements: Condition monitoring programs require continual review and update to ensure maximum reliability and benefits. In addition, the implementation of any new technology such as FT-IR is bound to require change as it is adapted to the equipment maintenance environment. While much work was done to adapt FT-IR prior to its introduction in the Army, new fuels and lubricants have required modification to several of the search areas and algorithms.

Fuel Dilution: Fuel is perhaps the most difficult parameter to measure due to its similarity to lubricating oils. Engine fuels can consist of a wide variety of straight chain and branched aliphatic compounds, aromatic compounds and other substituted compounds blended to produce a desired set of physical properties. As the composition and viscosity of a liquid fuel can vary greatly, any single analytical method to detect fuel will suffer from serious limitations. In addition, the conditions in an engine will cause the overall composition of the fuel to change because of both partial combustion and distillation of lighter components. FT-IR determines fuel contamination by measuring the absorbance bands of specific components in the fuel. The fuels studied in this program are diesel and jet fuels (JP4, JP5 and JP8).

Jet fuels are similar to diesel fuels and all consist of different compounds, additives and reformates. A marker band typical in fuel contaminated oil samples was found at 810 cm^{-1}. This absorbance band is typical for out-of-plane bending of two adjacent hydrogens in a para-substituted aromatic ring. For condition monitoring, the exact identification of specific compounds is not relevant. As the fuel marker is a narrow, specific band, restricted baselines are used. Baseline points are taken as the minima between 835 to 825 cm^{-1} (left) and between 805 to 795 cm^{-1} (right). The area is measured over the range of 815 to 805 cm^{-1}.

Experience has shown (and reported elsewhere) that some diesel and jet fuels are formulated with little or no aromatic content. These fuels lack the marker band (810 cm^{-1}) discussed above. To overcome the sometimes poor reliability of fuel measurement, a new approach was developed. Instead of a single measurement point, several fuel peak areas are integrated into a single measurement (Figure 1).

The specific areas of interest were determined by gas chromatograph infrared (GC-IR) analysis of several fuel types. The GC separated the fuel into its separate components e.g., 1,2,3 trimethylbenzene, ethylbenzene, indane, isopropylbenzene, etc. The individual infrared responses of the major fuel constituents were compared to infrared responses in contaminated and uncontaminated Army oils. This study suggested a series of specific areas depending on the lubricant type. By choosing multiple measurement points, it is

hoped that the normal variance in fuel constituents will not adversely affect the reliability of fuel measurement. Please note, the chemical constituents of lubricants impact the fuel areas chosen and different areas are integrated for petroleum and ester oils.

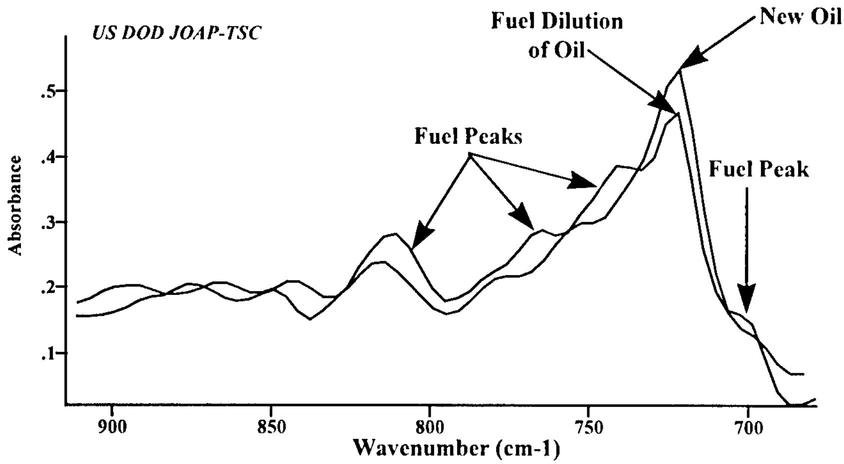

Figure 1: Fuel measurement areas in a Mil-L-2104

It is important to remember that trending lubricant components also indicates fuel contamination, because as fuel contamination increases, the levels and thus infrared response of the lubricant components decrease. A drop in the trend of other lubricant parameters can be used in conjunction with the fuel marker bands to improve the indication of fuel contamination. In addition, the "incorrect fluid" parameter for a polyol ester measures the presence of a petroleum fuel as efficiently as a petroleum oil. The total response of the FT-IR should be evaluated when diagnosing a potential fuel problem.

Base Stock Breakdown in Polyol Ester Oils: Base stock breakdown in polyol ester synthetic lubricants is presently monitored in two regions. First, the region around 3535 cm^{-1} indicates that the breakdown products are mostly composed of weakly hydrogen bonded alcohol or acid groups. Here, base stock degradation is measured over the range 3595 to 3500 cm^{-1}. A single baseline point for this measurement is taken at 3595 cm^{-1} to eliminate any interference from water contamination because as water contamination increases, the baseline shifts accordingly. The second area is in the hydrogen bonded O-H stretch region (symmetric and asymmetric) and is due to the numerous hydrogen bonded by-products formed from the polyol ester lubricant breakdown. The measurement algorithms initially recommended were the same as that for the hydrogen bonded O-H stretch vibrations of liquid water in petroleum based lubricants—over the

range of 3500 to 3150 cm^{-1} with a general baseline over the range of 4000 to 2000 cm^{-1}. The area included the ester overtone band at 3460 cm^{-1} and the antioxidant band (s) at approximately 3380 cm^{-1}. Since all polyol esters had these bands, the contribution from these peaks was essentially uniform and the petroleum 3500 to 3150 cm^{-1} area was used for simplicity.

Some of the new polyol ester blends approved for use in the military do not have the antioxidant peaks. The absence of these peaks impacts the overall reading (lower values). The proposed new area is from 3330 to 3150 cm^{-1} with a general baseline over the range of 4000 to 2000 cm^{-1} (Figure 2).

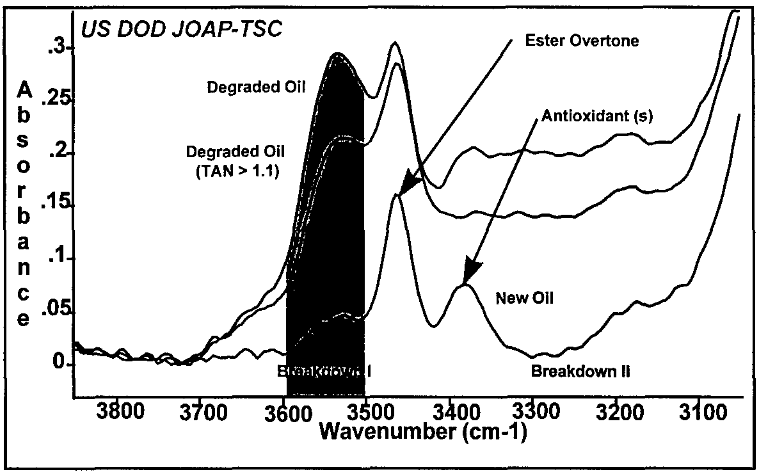

Figure 2: Breakdown in polyol ester lubricants

Solvents: Heptane, a flammable solvent, is used to clean the transmission cell between samples. One Army base suggested a terpene based, non-flammable solvent, Electron, be evaluated for cell cleaning to reduce their waste disposal requirement. Electron is already used in the AOAP for sample stand cleaning in atomic emission spectrometers. Using this solvent doubles the cleaning times for most lubricants and triples it for hydraulic fluids. The base felt the additional time was acceptable for their purposes. Heptane is still used for cleaning at the end of the day to ensure no terpene residue remains. As an added note, polyethylene IR cards are being evaluated as a solventless solution for FT-IR sample introduction [8,9].

New Analysis Capabilities: In early 1995, the first FT-IRs were placed in Army laboratories. The initial methods development focused on Mil-L-2104 and Mil-L-23699, the primary fluids in the Army (84%). Since implementation, the Army has requested methods for hydraulic fluid analysis (petroleum and phosphate ester based). In addition,

the Army has recently changed the lubricant used in AH6 main transmission and tail rotor gearboxes to a phosphate ester.

Petroleum Hydraulic Fluids: Fluids with EP or TEP additives inhibit the clear observation of either a hydrogen bonded OH stretch or non-hydrogen bonded OH stretch. Water contamination in these fluids is observed as a baseline rise or offset (Figure 3) but does not show the evidence of Tyndal—particulate or colloidal scattering as seen with insolubles (soot) which show a tilted baseline offset. Also note that soot should not be present in these fluids.

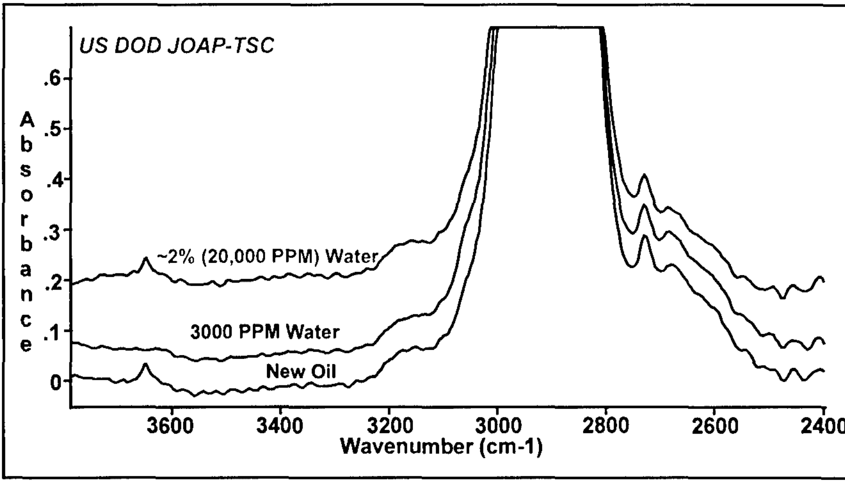

Figure 3: Water in EP fluids

During equipment operation, the organic compounds of all lubricants are exposed to high temperatures and stresses in the presence of oxygen and/or water, resulting in the formation of partially oxidized compounds. These acidic by-products can be oxidation, nitration or sulfate compounds. The FT-IR individually measures these by-products.

Oxidation By-Products: FT-IR determines the level of oxidation by-products by a general response in the carbonyl region. In this region, infrared energy is absorbed due to the C=O stretch from ketones, esters, carboxylic acids, carbonates, aldehydes, anhydrides, and amides, to name a few. Monitoring this region is thus a direct measurement of the oxidation. The infrared area is measured over the range of 1800 to1670 cm^{-1} with two minima taken as the baseline correction. The left baseline (high wavenumber side) is taken as the minimum over the region of 2200 to 2000 cm^{-1} and a right baseline (low wavenumber side) over the region of 600 to 550 cm^{-1}. Very few compounds found in new and used petroleum lubricants have significant absorbance in these baseline areas

(Figure 3). This baseline definition corrects for any offset and tilt due to soot and particulates. The same area is used for petroleum lubricants and hydraulic fluids. The petroleum hydraulic fluids tend to have sharper, tighter bands than the petroleum lubricants—this is may be due to lower concentration of additives in the hydraulic fluids.

Sulfate By-Products: Sulfur compounds are found in some crudes and as additives in some fuels (antioxidants and biocides for storage) and petroleum oils (EP additive). These compounds increase the production of varnishes and sludges and generally degrade fluid performance. Sulfates are measured over the region of 1180 to 1120 cm^{-1} using the general 2000 to 600 cm^{-1} baseline. Over this measurement region, the most probable absorption group will be either from an SO_2 symmetric stretch or the SO_3 stretch from a $C\text{-}SO_3\text{-}H_3O^+$. Various levels of oxidation and sulfate by-products are shown in Figure 4.

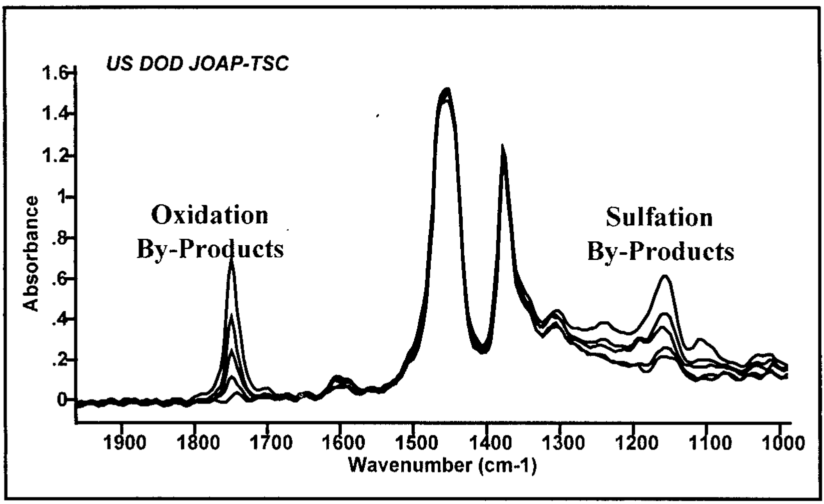

Figure 4: Oxidation and sulfate by-products

Nitration By-Products: In addition to oxidation and sulfation, nitration by-products can also develop when organic compounds are exposed to high temperatures and pressures n the presence of nitrogen and oxygen. While nitration by-products have been observed in petroleum lubricants, they have not been observed to date, in hydraulic fluids.

Phosphate Ester Hydraulic Fluids: These fluids also contain EP or TEP additives which inhibit the clear observation of either a hydrogen bonded OH stretch or non-hydrogen bonded OH stretch. Water contamination in these fluids is also observed as a baseline offset, however, excessive water may be seen in the traditional hydrogen bonded OH

stretch region. As for other failure modes, there have been insufficient samples for proper characterization and methods definition.

Other Fluid Systems: The JOAP-TSC also has developed preliminary methods to detect fault mechanisms in other machinery fluid systems such as coolants (silicate esters (coolanol), phosphate ester lubricants, refrigeration lubricants and their respective refrigerants etc. More samples with some fault progression are required for completion of the methods.

Closing: The downsizing of today's military forces, reduced budgets and reduced equipment usage dictates that only state-of-the-art technology be employed for equipment condition monitoring. The use of FT-IR by AOAP increases the overall maintenance posture, improves operational readiness, enhances safety and saves valuable resources—a quantum jump for the Army. And most importantly, it supports the needs of the soldier-in-the-field.

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Validation of a FTIR Spectroscopy Method for Measuring and Monitoring Fuel Dilution in Lubricating Oils

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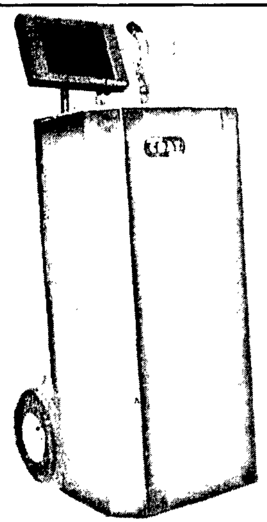
Abstract: A FT-IR based fuel dilution analysis system was validated for long term reliability and precision. Frequency shift and spectral reproducibility tests showed that the instrument could operate for up to 10 months without maintenance. Changes in ambient temperature and humidity levels and the proximity to mechanical and acoustic noise generators did not affect the performance of the instrument. This was accomplished due to the methodic analytical procedures, data analysis and isolation devices developed and employed. The system was calibrated using actual used oils and fuel dilution values determined by the standard ASTM Gas Chromatography method. The calibration model developed with multivariate algorithms was able to predict fuel in SAE 30, 40, 50 and Mil-L-9000 engine oils down to 0.4% dilution.

Key Words: Condition monitoring; Failure prevention; FT-IR; Fuel Dilution; Infrared Spectroscopy; Oil Analysis; Used Lubricating Oil;

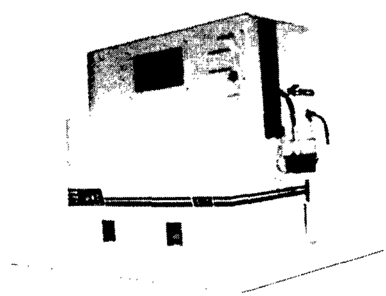
Introduction: Lubricant condition monitoring programs are widely accepted as preventive measures to premature machinery failures [1, 2]. Analytical testing of lubricating oils is an efficient cost-effective tool commonly used to track fluid degradation and assess operating conditions of mechanical equipment. The results when properly interpreted can be useful for the detection of mechanical faults in critical equipment before equipment failure. A successful implementation and application of such programs however require *a)* the acquisition of data that provides information pertaining to the performance status of the monitored lubricant, *b)* a reliable instrumentation, *c)* a robust and rapid analytical method to detect and identify the problems and provide the necessary corrections. Machinery failure prevention based on

lubricant condition monitoring is applicable to industries such as paper mills, metal processing and petroleum refineries, which rely on high performance lubricants.

The objective of continuous condition monitoring programs is to perform fast and reliable analyses for on-time correction of problematic situations. This objective is often defeated by delayed analytical results of third party laboratories. One case that well illustrates this situation is the analysis of fuel dilution in diesel engine lubricating oils on board naval ships. The seepage of fuel into the lubricant reservoir can induce deleterious changes that inevitably affect the performance of the fluid and the engine. As part of its failure prevention program, tests for fuel dilution in used diesel oils represent a significant element of the Oil and Coolant Condition Analysis Program (OCCAP) of the Canadian Forces Navy. The currently accepted ASTM standard procedure for determining fuel dilution in lubricating oils is based on Gas Chromatography (GC) methods. GC test equipment requires daily calibrations, which can take from one to several hours depending on the number of standards used for a particular testing procedure. Furthermore, samples have to be shipped to land based GC laboratories thereby delaying the implementation of the necessary corrective measures.



The C1 model is ruggedized mobile unit



The C2 model is a bench top version for use in controlled environment

Figure 1: Two models of the COAT system used for fuel dilution analysis.

In a previous report [3], we have described the design and calibration of a Fourier Transform Infrared (FTIR) based analytical instrument for measuring fuel dilution in lubricating oil. The method is incorporated into a Continuous Oil Analysis and Treatment (COAT®) system (Fig.1) and calibrated against fuel dilution data obtained from an

external laboratory using the standard ASTM D3524 gas chromatography (GC) method. The FTIR method is rapid, accurate, and could be used on-board ship to provide immediate results. There are no hazardous chemical reagents, no sample burning, no lengthy sample preparation involved and a daily calibration is not required. Furthermore, advanced data analysis tools such as multivariate algorithms of partial least square (PLS), can be applied to the development of robust calibration models thereby increasing accuracy and reliability in the assessment of fuel dilution in lubricants. This paper describes the validation of the FTIR based system for fuel dilution analysis under the conditions described below.

Instrumentation and Procedures: The validation was carried out using the ruggedized mobile version of the COAT® system (Fig. 1). The system was operated for ten continuous months without maintenance. The testing proceeded as follows:

1. Evaluation of the instrument reliability in terms of frequency shift and spectral reproducibility. Testing environments were *a)* temperature controlled laboratory and 'plant floor' machinery control room with low acoustic noise, mechanical vibration, and humidity levels; *b)* 'plant floor' exposed to temperature and humidity level changes, high acoustic noise, and significant mechanical vibration level.
2. Evaluation of the calibration for long term stability and method consistency.
3. Evaluation of the performance of the FTIR based fuel dilution method by participating in a Round-Robin test setup for the GC method (ASTM D3524). The FTIR results are compared to GC data from approximately nine different commercial and governmental GC laboratories. Unknown samples were predicted using the calibration and system parameters established 10 months earlier. A new calibration was also built and the predictions were compared to the existing calibration results.

Results and Discussion: A formulated polyalphaolefin (PAO) based synthetic oil was used as reference for the evaluation of the COAT® system and the calibration method. The reference oil spectra (Fig.2) provided information on pathlength change, cross-contamination, cell filling and presence of contaminants in the lines or on the cell crystal surfaces. The absorbance band around 892 cm-1 was mainly used for frequency shift and spectral reproducibility tests.

1. System Validation: Instrument reliability tests conducted in laboratory and machinery control room with stable temperature and humidity levels showed the system was not affected by "normal" operating conditions. Figure 3 represents the monitoring of absorbance bands at 892 cm^{-1} from the spectra of the PAO reference oil. The error on the frequency after 40 weeks of operation is ± 0.01 cm-1. The frequency stability of the COAT® system is made possible due to corner cube mirror technology that allows permanent alignment of the infrared interferometer. This feature is desirable especially for instruments designed to be mobile because a frequency shift of the order of 0.1 cm-1 can induce up to 0.2 % error. Spectral reproducibility tests were conducted by evaluating the residual spectra of reference oils and comparing the peak height at 892 cm-1. After 40 weeks of operation, spectral error was in the order of 3 milli absorbance unit

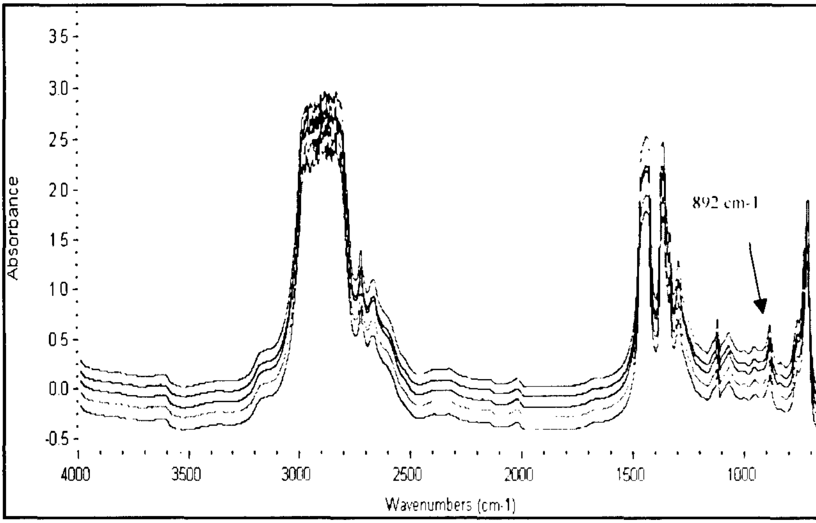


Figure 2: Infrared spectra of reference synthetic oil

and there was no sign of increase. These results demonstrate the long-term reliability and stability of the COAT® system, an important requirement for a maintenance free analytical instrument.

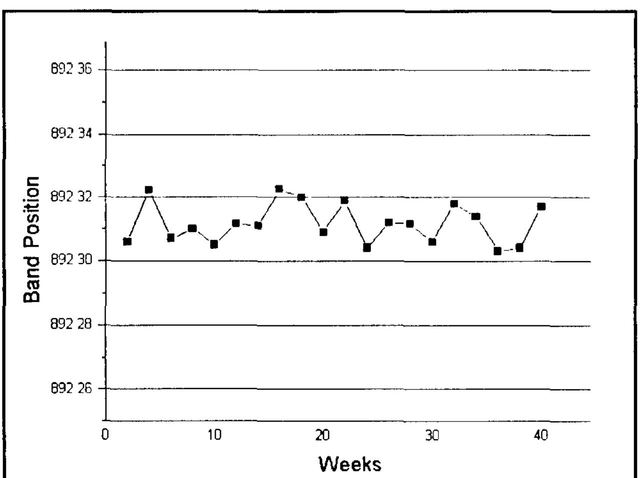


Figure 3: Frequency reproducibility of the COAT® system

The performance of the system was however affected when operated on the plant floor where vibration and noise levels exceeded 20 Hz and 3k Hz, respectively. The situation was corrected after mechanical dampening, insulation and noise barriers were installed. Figure 4 shows the results obtained before and after noise and vibration control devices were installed. Scan rejections due to bad data was eliminated and the precision on the measurements was greatly increased. The additive level was monitored with accuracy (± 0.02 %) within the upper and lower limits required for this particular application. The varying humidity levels on the plant floor were compensated for by including an algorithm in the sampling procedure to automatically record a background spectrum before every sample. This is made possible due to the proprietary movable transmission flow-through cell sampling accessory of the COAT® system [3].

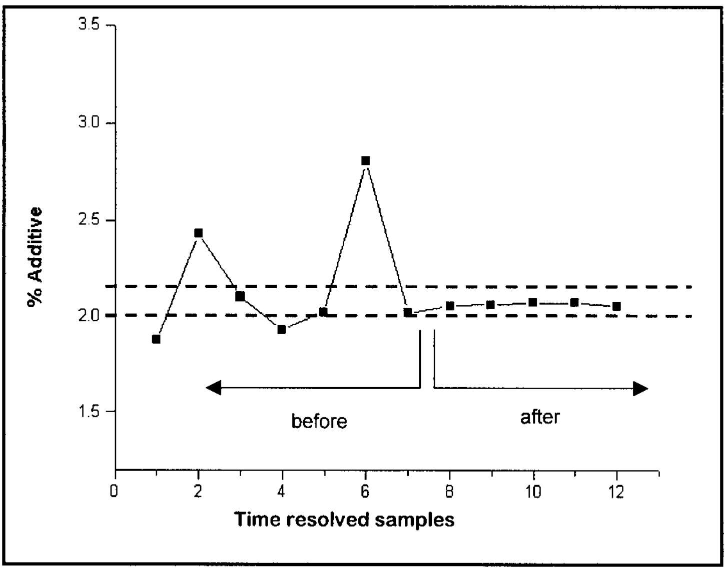


Figure 4: Monitoring of additive levels before and after system isolation.

2. Validation of Infrared Fuel Dilution Method: The quantitative calibration method for fuel dilution by infrared is based on multivariate statistical analysis. The application of partial least-squares (PLS) modeling to both mid and near infrared data analysis is well documented [4, 5]. A number of steps were considered for the development of a robust calibration since the model is developed against GC fuel dilution data, a method with considerable inherent sources of errors. Furthermore, for reasons we have previously reported [3], the calibration standards are all actual diesel fuel contaminated used oils obtained from the Canadian Forces Navy. Although full spectrum features can be used when working with PLS, due to the nature of the standards and the reference data, we have identified a unique spectral region that best describes the fuel dilution status of all

standards [3]. In the mid-infrared, diesel fuel appears around 810 cm-1, however the exact position of the band is affected by the lubricant source, type (synthetic or petroleum based etc...) and lubricant. Figure 5 shows the scaled spectra of 5 lubricants with the same fuel dilution value of 2.5%. To minimize the model

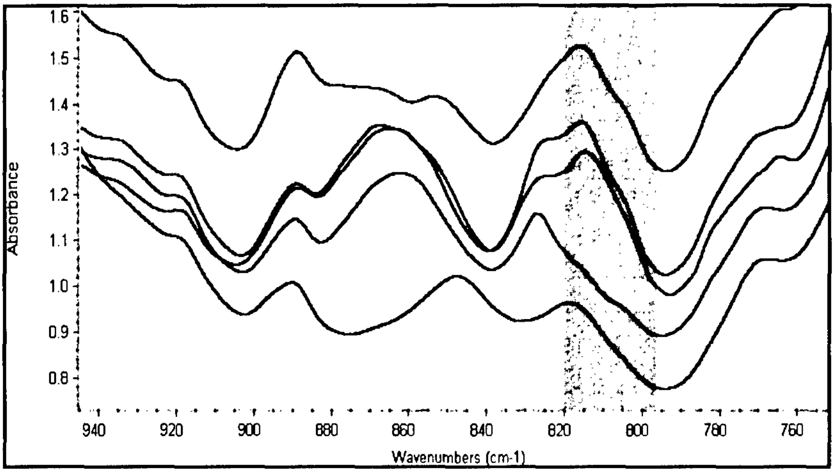


Figure 5: Grayed area illustrates different peak shapes around 810 cm-1 band. All 5 spectra have a fuel dilution value of 2.5%.

sensitivity to lubricant and fuel sources, the calibration standards are balanced so that the source and type information becomes redundant and is therefore neglected by PLS. This is important for naval applications where ships in deployment may acquire lubricants and diesel fuels from various sources. Using a narrow spectral region with base point anchors minimized non-linearity caused by "normal" instrument drift and the presence of contaminants such as soot in the standards. With this approach, the automatic baseline correction feature of the software becomes more reliable. Figure 6 shows the calibration curve obtained for diesel fuel dilution using 7 loading factors decided upon after a cross-validation evaluation (R^2= 0.97 and STD = 0.25). It is worth mentioning that the accuracy of this calibration is dependent on the accuracy of the associated reference GC method. The performance of the FT-IR fuel dilution method during the Round-Robin evaluation of the GC method (ASTM D3524) has proved the method's capability to quantitate fuel dilution in both used and new oil. As expected the calibration model developed with fuel contaminated used oils could not predict the fuel content of new oils and vis versa. The new and used oil samples were predicted using the appropriate calibrations. Table 1 shows the prediction results and statistics for new oils. Five new oil samples were spiked with fuel and their predictions compared to the mean triplicates of non-spiked samples. The results show calibration consistency and accuracy. The overall prediction error for the non-spiked samples was 0.05 % while error between the calculated and the predicted spiked samples was 0.08% fuel dilution.

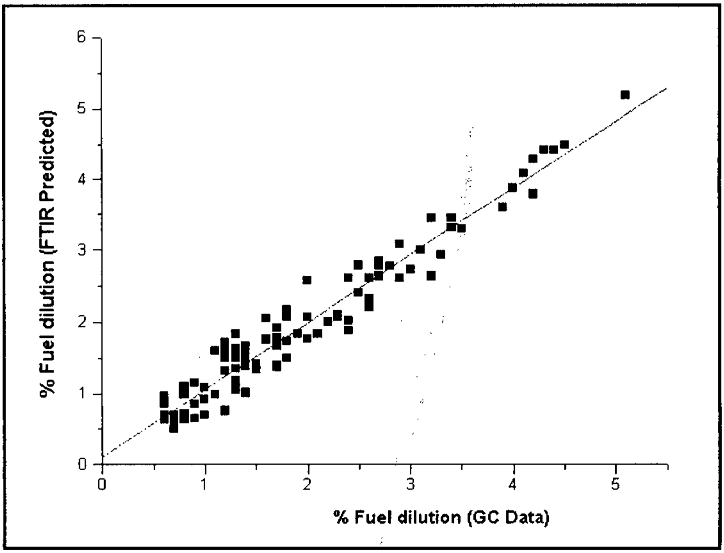


Figure 6: Calibration curve showing the correlation between the FT-IR predicted fuel values and the reference data

Table 1: Prediction of fuel dilution in new oil samples

			Spiked Samples		
Sample code	% Fuel[1]	STD	Prediction	Calculated	STD[2]
NO7	1.13	0.04	3.68	3.89	0.11
NO8	3.18	0.03	5.43	5.71	0.14
NO11	1.79	0.13	4.38	4.50	0.06
NOS1	0.99	0.01	3.31	3.44	0.06
NOS2	2.02	0.04	4.56	4.59	0.02

1. % Fuel refers to the mean of triplicate analyses

2. STD[2] is the standard deviation from the mean of predicted and calculated fuel values

Similar results were obtained for the prediction of used oil samples. The overall error on the prediction of non spiked used samples was 0.13% fuel value while the comparison between the predicted spiked samples and the calculated values shows an overall error of 0.25% fuel.

Table 2: Prediction of fuel dilution in used oil samples

Sample code	% Fuel[1]	STD	Spiked Samples		
			Prediction	Calculated	STD[2]
UO1	7.04	0.40	9.22	9.94	0.36
UO2	3.79	0.12	6.04	6.40	0.18
UO3	2.46	0.08	4.72	5.07	0.18
UO4	2.22	0.10	3.92	4.74	0.40
UO5	2.62	0.15	5.28	5.62	0.17
UO6	1.59	0.00	4.43	4.50	0.04
UO9	0.52	0.04	2.61	3.32	0.40

1. % Fuel refers to the mean of triplicate analyses
2. STD[2] is the standard deviation from the mean of predicted and calculated fuel values

Long term stability tests of the calibration model were conducted by recording and predicting 40 samples not included in the calibration after 6 and 10 months. The global prediction error of the model for both predictions remained around 0.4 % fuel. Prediction error due to calibration drift was significant towards the end of the testing period. To minimize this source of error, the calibration should be revised every 4 to 5 months by adding new standards in order to actuate the standards pool with respect to actual lubricants and fuel in use.

Conclusion: The validation of the COAT® system for fuel dilution analysis was successful. Fuel dilution is measured in 5 minutes or less without jeopardizing accuracy. Furthermore, there are no hazardous chemical reagents, no sample burning, no lengthy sample preparation involved and daily calibration is not required. Although the validation was conducted on land, the results described herein can be reproduced on board ship. A tremendous gain is envisaged analyticaly where the operator has a total control over the lubricant monitoring process. The historical data of the lubricant is available and corrective measures can be applied as new data that reflect its actual status is acquired. The stability of the system will provide accurate data for up to 5 months before any calibration correction is necessary.

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Molecular Condition Monitoring in the Commercial World:
Objectives and Applications of FT-IR Analysis

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Abstract: Chemical and physical analysis of lubricants and hydraulic fluids is a common tool employed in equipment condition monitoring programs. Periodically checking these fluids for common contaminants and breakdown products allows a fast diagnosis of the general "health" of a machine or component, and thus permits maintenance activities effectively directed or deferred as necessary. A variety of different wet chemical and spectroscopic tests have been developed and applied to meet these needs. Condition monitoring of engine oils is perhaps the most common, with spectroscopic wear metal analysis complimented by molecular analysis by Fourier Transform Infrared (FT-IR). Much information has been presented in the past towards applying FT-IR analysis to engine lubricant condition monitoring. However, analysis of engine lubricants may only be a part of, or entirely unrelated to, other condition monitoring operations. Here, we will present additional information, examples, and statistical analysis of non-engine lubricants and machinery enrolled in commercial condition monitoring programs.

Key Words: Condition monitoring; Fourier transform infrared; contamination; degradation; lubricant properties; petroleum lubricants; synthetic lubricants.

Introduction: Condition monitoring of common lubricants is employed to diagnose the general "health" of a machine or component. Analyzing for common, known fault signatures, such as excessive wear metals, lubricant degradation, or lubricant contamination generates a fast and simple diagnosis of the condition of the lubricant, and thus the condition of the machine. This information allows timely and necessary maintenance to be either scheduled or deferred, as dictated by the machine condition. This approach, generally referred to as "condition based maintenance", is widely employed to maintain expensive mechanical systems while minimizing routine maintenance costs and oil consumption.

Condition monitoring has found the widest application in the protection of mobile equipment, most commonly diesel engines. Atomic spectroscopy was first applied in the analysis of wear metals in railway engines in the early 1940's. [1] Since that time, spectroscopic wear metal analysis of used diesel crankcase oils has become the most common instrumental technique employed in condition monitoring. Both original equipment manufacturers and larger customers today will specify allowable levels and

trends of wear metals and elemental additives in the crankcase oils. These levels and trends will be determined by a combination of information and recommendations from the engine manufacturer, and can be modified by other factors such as age, usage patterns, and previous maintenance. Elemental analysis is often supplemented by a variety of other physical and spectroscopic measurements, such as FT-IR spectroscopy. Many manufacturers will specify allowable limits and trends in their engines based on infrared spectroscopy, and at least one company has developed and received a patent for a dedicated on-engine, infrared based oil condition sensor. [2]

While much work has been done on the application of FT-IR spectroscopy in engine condition monitoring, engines represent only a portion of the total range of machinery enrolled in commercial condition monitoring programs. Effectively applying FT-IR analysis to systems other than engines requires the same initial planning and data gathering steps as would be required in applying wear metal or other analysis tools. Three questions first need to be answered: 1) what are the characteristic faults or failures that can be detected? 2) What is the normal variance or distribution of these measurements? 3) Does the measurement have sufficient precision to indicate these failures? While past work on engine lubricants can be used as a starting point, straight application of infrared methods developed for crankcase lubricants will produce an ineffective evaluation. This may lead to the inaccurate conclusion that infrared spectroscopy is not beneficial for non-engine lubricant monitoring, when in fact, the crankcase oil analysis methodologies are not beneficial for gear boxes and hydraulic systems.

Besides routine condition monitoring of lubricants and fluids in-use, the commercial condition monitoring laboratories will work with machinery and lubricant manufacturers in evaluating formulation performance from real-world field data. While much work is applied before a formulation is released, it is most often supplemented from a wider range of equipment, conditions, and usage patterns than is possible in a laboratory test bed. In this area, routine FT-IR measurements are used in conjunction with other physical measurements on the performance of the lubricant in order to better understand which contaminants and breakdown products contribute most to the overall degradation of the lubricant characteristics.

Petroleum EP Fluids: In plant machinery gear boxes, the most common faults which occur are contamination of the lubricant by water, and degradation of the lubricant by a combination of pressure and heat generated at the gear tooth contact points. There can be many other faults specific to the environment of the machinery that can be detected by FT-IR spectroscopy. Some of these can include dirt contamination in an ore processing line, or contamination from cutting fluids in an automated machining line. However, we will only consider the general contamination and degradation processes found in the majority of these systems.

As water is the most common compound found on the surface of the earth, it too is the most common contaminant in gear drives. Previous studies demonstrated that the infrared analysis methods developed for petroleum based crankcase oils were unsuitable for synthetic polyol ester turbine lubricants. [3] This is due to differences in the interactions

between the water and the detergent/dispersent package in crankcase lubricants, versus interactions between the water and the synthetic lubricant package in turbine lubricants. While petroleum based gear lubricants may expected to respond in the same manner as the petroleum based crankcase lubricants, the extreme pressure (EP) additives in gear lubricants interact with contaminating water in yet another manner. Figure 1 shows this effect in an example of a petroleum based EP oil with water contamination. In these fluids, water contamination is detected by a constant offset in the baseline of the spectrum. The appearance of a distinctive OH stretch peak only becomes noticeable in extreme cases, as seen in Fig. 1. The infrared response for water contamination in a petroleum based EP hydraulic fluid is similar to that of the gear lubricants.

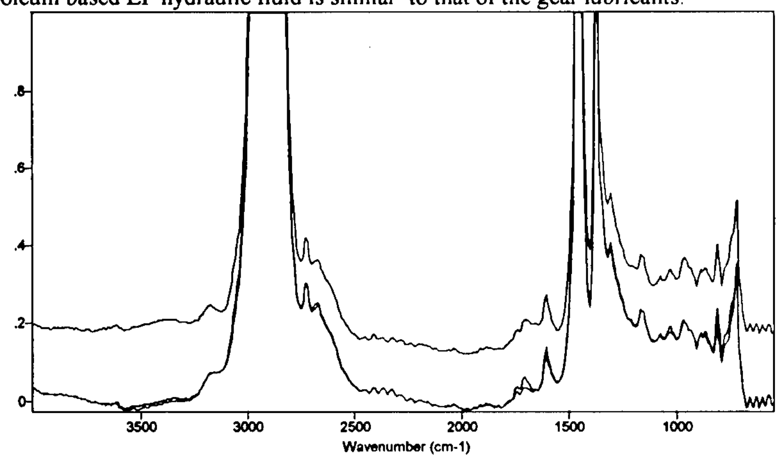

Figure 1. Water Contamination in EP Oil

In addition to water contamination, degradation of the oil due to the localized high pressures and temperatures generated will occur. Interaction with atmospheric oxygen and nitrogen under these conditions will produce oxidation and nitration in the oil. Figure 2 shows some examples of the buildup of oxidation products in some EP additive gear lubes. While those familiar with the infrared spectra of various synthetic lubricants may be tempted to identify the top two spectra as synthetics (based on the strong carbonyl band), these were originally EP petroleum lubricants like the lower spectra. In addition to the high infrared oxidation readings, oxidative degradation of the top lubricants was confirmed by high TAN (Total Acid Number) measurements.

In the case of oxidation, nitration, and other degradation products, two different approaches can be taken towards determining normal and abnormal values. The first was hinted in the preceding paragraph: correlation of the infrared spectrum to a known physical measurement. While this has been demonstrated in the past, [4] generating and maintaining these correlation routines adds an additional burden to the condition monitoring operation. As will be demonstrated later, infrared spectroscopy is able to measure all the individual properties that determine the bulk physical nature of the oil. With this, then it only becomes necessary to determine the normal distribution of the

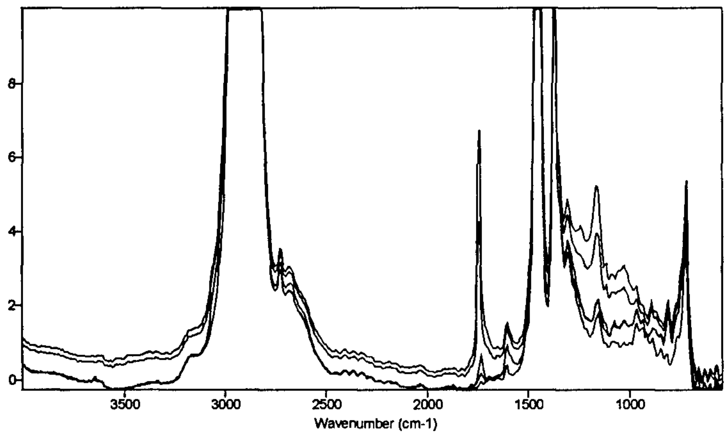

Figure 2 Oxidation Degradation of EP Oils

oxidation, nitration, and other degradation products that can be measured by FT-IR in these lubricants. Figure 3 shows the distribution profiles of the infrared measurements in a small population of EP gear oils. While not presented or proposed as strict limits in EP based gear box lubricants, the distribution profiles clearly show how normal (low to no degradation) and abnormal (excessive degradation) values can be discerned.

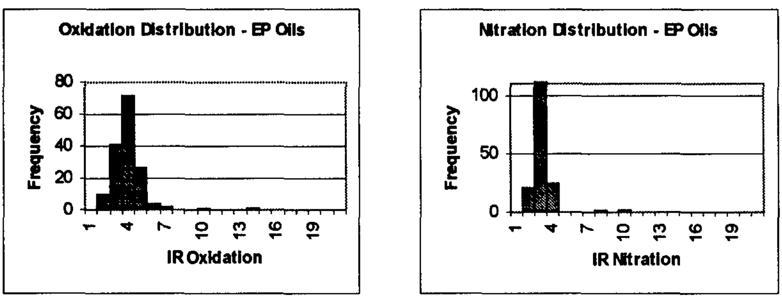

Figure 3. Oxidation and Nitration Distribution Profiles in EP Oils

Synthetic EP Fluids: Often, petroleum based lubricants and hydraulic fluids are unsuitable for some applications. In these, a higher degree of protection, wear resistance, inertness, or fire resistance is needed than can be obtained in a refined petroleum. Quite a large number of different formulations are available, ranging from simple synthetic hydrocarbons through very specialized chlorofluorocarbon ether lubricants. However, most of the synthetic lubricants are ester based compounds, and can be further divided into simple esters and phosphate based esters. [5] Starting with a synthetic based fluid, additional additives are blended to achieve the final degree of performance desired for a given application.

Extreme pressure additives are also commonly used in synthetic lubricants to improve performance under heavy loads. These blended synthetic fluids interact with water similar to the case of the EP additive petroleum oils. As seen in Fig. 4, varying degrees of water contamination is exhibited by a general baseline offset of the infrared spectrum of the sample. Here, the bottom traces represent oils with no water contamination, the middle set of traces represent water contamination in the 1000 to 2000 ppm range, and the top spectrum represents a sample that was found to have 9% (90,000 ppm) water. Note that this water contamination level is far in excess of saturation point of the oil, and the level was determined by the volume of water that settled out on standing. Thus, there is not a linear relationship in the infrared spectra between the lower levels of water contamination and this extreme case. However, if the objective is to "catch" water contamination in the 1000 ppm range, then establishing a perfect linear relationship for such an extreme condition becomes unimportant.

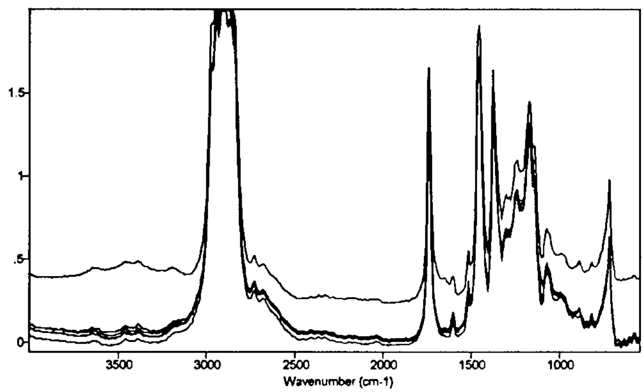

Figure 4. Synthetic EP Oils, Varying Water Contamination.

For the measurements of the chemical degradation of these synthetic fluids, such as from oxidative degradation due to heat, pressure, and oxygen, additional knowledge is needed. As different starting synthetic compounds will break down to form different products, then a simple, "one-size-fits-all" approach to measuring these degradation products will inevitably miss some cases of excessive breakdown while generating too many false alarms in other fluids. For example, simple and polyol esters will break down to form the starting organic acid and alcohol. Here, detecting this type of lubricant breakdown is performed by measuring the areas of the infrared spectrum where these functional groups appear. [3] Phosphate esters will break down to form organic acids, alcohols, simpler organophosphate compounds, and phosphate acids or salts. As the phosphate groups are generally strong infrared absorbers, a change in this area may be taken as a guide toward lubricant breakdown. Discussing all the different chemical breakdown infrared profiles for all the different classes of synthetic lubricants is beyond the range of topics that can be discussed in this limited paper. Work is progressing on further characterizing these fault signatures, and results will be presented later.

Lubricant Performance Research: Besides providing routine condition monitoring services, commercial laboratories are often tasked by lubricant manufacturers to provide field performance data on their (and their competitors) lubricants under real-world conditions. This research usually involves investigation of the performance of various blends and additive package levels, relating the field information to their own database of lubricant physical characteristics. One physical characteristic often used by lubricant manufacturers, blenders, suppliers, and purchasers, is the total base number (TBN) of a lubricant. This number is typically used to expresses the level or activity of the additive package, with higher numbers typically providing a greater degree of protection to the buildup of acidic breakdown products and contaminants. Previous work showed the power of FT-IR analysis, in combination with the mathematical analysis techniques of Principle Component Regression / Partial Least Squares, in accurately predicting the viscosity of railway lubricants based on the infrared absorbance spectrum. [4] While FT-IR spectroscopy is capable of measuring all the individual chemical compounds, and the interactions between the different chemical compounds, which determine the overall physical characteristic of a lubricant, these tools are often first needed to uncover the complex relationships between these compounds and complexes.

Based on this and other successful applications of FT-IR and PCR/PLS, one laboratory studied the factors by FT-IR spectroscopy that influence TBN in high-speed diesel crankcase lubricants. To verify that components measured in the infrared spectrum could be correlated to the physically measured TBN, a PCR/PLS "training set" of ~150 used crankcase lubricants from different equipment and applications was collected. This was then used to test the ability of FT-IR spectroscopy to measure all the important components in the oil, which affect the TBN. Figure 5 shows the correlation between the TBN as predicted from the FT-IR spectrum (y-axis) versus the physically measured TBN. While some scatter is seen across the range, the number of outliers was not judged significantly different from two independent physical TBN titrations.

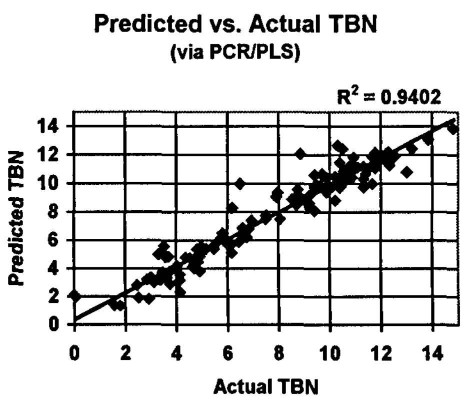

Figure 5. Predicted TBN by IR vs. Measured TBN

With this data demonstrating that FT-IR spectroscopy is recording all the various compounds and their interactions which affect TBN, further study was done to determine which chemical or functional groups contributed the most to the change in the TBN. These factors, presented in table 1, show that the additive package is very effective in interacting with, or neutralizing, oxidation and sulfation breakdown products formed in the oil. However, the surprise finding is that the nitration products contribute to the change in the TBN to a greater degree than the oxidation and sulfation products combined.

Component	Relative Importance in TBN (Additive = 100%)
Additive	100%
Nitration Products	73%
Oxidation Products	41%
Sulfation Products	9%
Oxidation / Additive Interactions	2%
Sulfation / Additive Interactions	0.5%
All Others	<1%

Table 1. Relative Contribution to TBN

This information can then be used to further investigate additive package performance, with the long-term goal of allowing "environmentally friendly" extended drain intervals without sacrificing engine protection. It should be pointed out however, that while FT-IR spectroscopy can successfully predict physical characteristics of a lubricant such as viscosity and TBN, research goals and routine condition monitoring goals often do not significantly overlap. As routine FT-IR analysis can measure all the individual components that affect the lubricant's performance, it then only becomes necessary to measure these individual components, and relate them to a normal or allowed range. Developing, maintaining, and cross-checking calibration and correlation sets to predict physical properties will add a significant amount of work to a condition monitoring operation. However, it will not significantly improve the initial objective of a condition monitoring operation: judging the condition of a lubricant, and thus the machine, as an aid in maintenance planning.

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Comparison of 100 Micron Transmission Cell and the 3M© IR Card for FT-IR Analysis of Military Fluids

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Abstract: The 100 micron transmission cell is the current method of choice for automated FT-IR analysis of lubricating and hydraulic oils. The transmission cell requires cleaning after each sample and thus use of a solvent. This paper outlines the preliminary results of a comparison between the 100 micron cell and the 3M© IR Card (microporous polyethylene substrate). Petroleum and polyol ester lubricating oils were used in the study. Statistical results and problems encountered are presented.

Key Words: Condition monitoring; Fourier transform infrared; FT-IR; polyethylene IR cards.

Introduction: The 100 micron transmission cell is the current method of choice for automated FT-IR analysis of lubricating and hydraulic oils [1]. The transmission cell requires cleaning after each sample and thus use of a solvent. This paper outlines the preliminary results of a comparison between the classic transmission cell and a solvent free approach for sample introduction—infrared (IR) Card. In this approach, the oil sample is applied to a microporous polyethylene substrate. The substrate simulates a 100 micron cell in that the same amount (thickness) of oil is absorbed into the substrate as would be in the 100 micron cell [2, 3, 4]. Use of an IR Card would eliminate the need for solvent; speed up the analysis time since no cell cleaning time or drying time is required; and virtually eliminate cross contamination since the Card is only used once. In addition, the simplicity of the Card lends itself well to minimal operator training, making the FT-IR even easier to operate. Sample analysis can be performed on as little as 20 microliters of sample.

Test and Evaluation: Used oil samples from ground and air equipment were analyzed concurrently by IR Card and 100 micron cell. The samples were analyzed on the same day to eliminate any change in laboratory conditions and further degradation of sample.

Settings on the FT-IR instrument were harmonized to obtain comparable results between the IR Card and cell e.g., the gain was lowered for the Card since the light beam does not have to penetrate two cell windows as with a 100 micron cell; the background reading is taken with an empty sample slot (no Card in place), etc. In contrast, the transmission cell may be in place for background readings. IR Card sample application and reproducibility are discussed in another paper [2].

Individual parameters in the various methods e.g. "petroleum", polyol ester", etc. were also harmonized to improve the comparison between the IR Card and cell e.g., the Card generates a slight baseline offset not seen with the transmission cell. Consequently, a minor modification of the soot analysis parameter (petroleum method) was required for the IR Card. The majority of the parameters in the petroleum and polyol ester methods remained unchanged.

For the most part, parameter readings were the same for both the cell and the Card, particularly for normal and marginal readings. For high parameter readings (high contamination or degradation), there tended to be a difference between the Card and the cell—the higher the reading, the greater the difference. The cell readings were almost always higher, suggesting a greater dynamic range. In this study, measurement linearity is quite reasonable within the current alarm limits.

Petroleum oil (Mil-L-2104): Oil samples from Army ground equipment and laboratory prepared samples were analyzed. This limited study included only 63 petroleum oil samples, insufficient for conclusive findings. However, the results are encouraging. The data is graphically presented in the figures below.

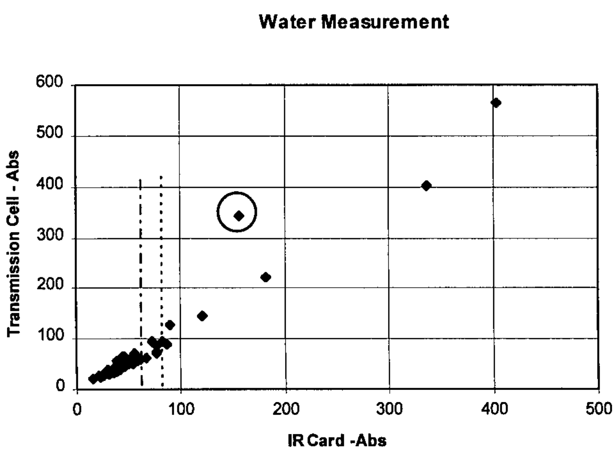

Figure 1: Comparison of Water Data
Water measurement coefficient of correlation = 0.97

Water: Notice sample 633 (circled) where the values are 342 Absorbance (Abs) units (cell) and 156 Abs (Card). Reanalysis of the sample provided no explanation of the differences between the cell and the Card. Please note, this was a heavily contaminated sample. The left vertical dashed line indicates 2000 PPM (65 Abs) water and the right indicates 5000 PPM (80 Abs).

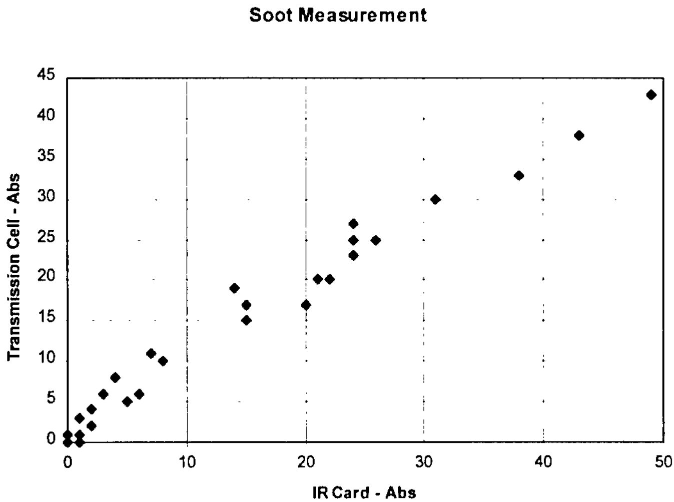

Figure 2: Comparison of Soot Data
Soot measurement coefficient of correlation = 0.99

Soot: Note, all samples were relatively free of soot. The current limit for heavy soot is 50 Abs.

Oil Degradation: Oil degradation by-products shown in Figures 3, 4 and 5 (oxidation, nitration and sulfation, respectively), have good correlation between the cell and the card. It should be noted that none of the samples were severely degraded. Current alarm limits are oxidation—18 Abs, nitration—14 Abs and sulfation—35 Abs.

Fuel: There were only a few samples with fuel contamination. Improvements in infrared detection for fuel contamination is ongoing for both the cell and the card.

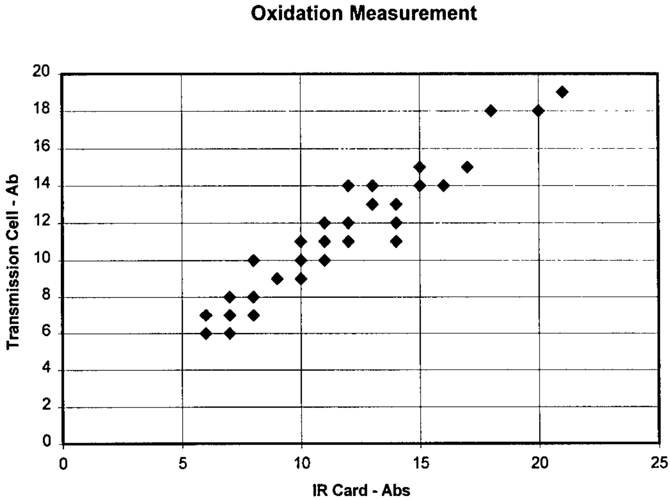

Figure 3: Comparison of Oxidation Data
Oxidation measurement coefficient of correlation = 0.97

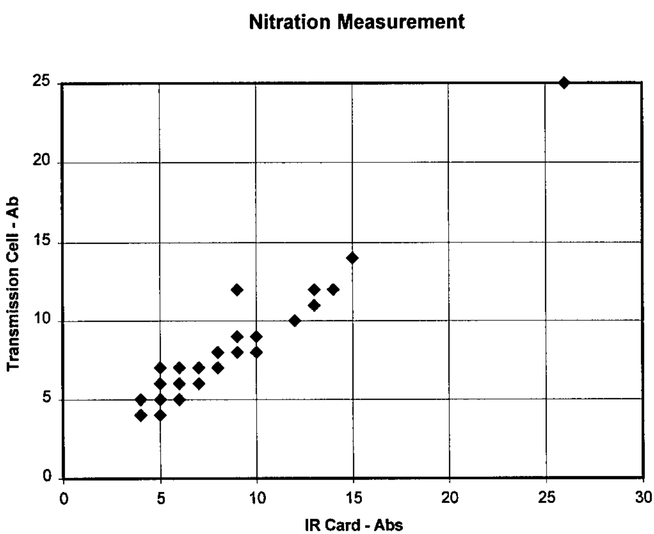

Figure 4: Comparison of Nitration Data
Nitration measurement coefficient of correlation = 0.97

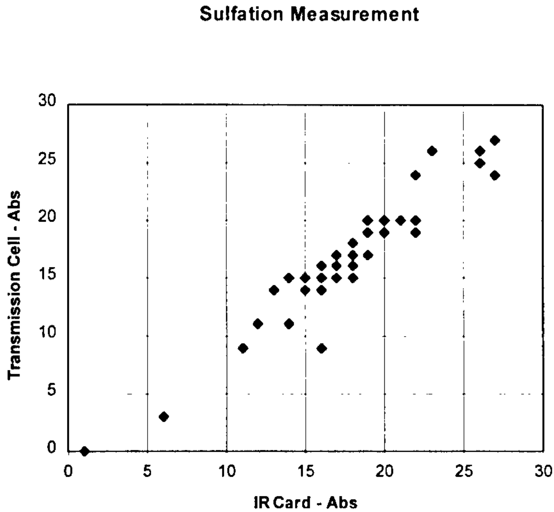

Figure 5: Comparison of Sulfation Data
Sulfation measurement coefficient of correlation = 0.95

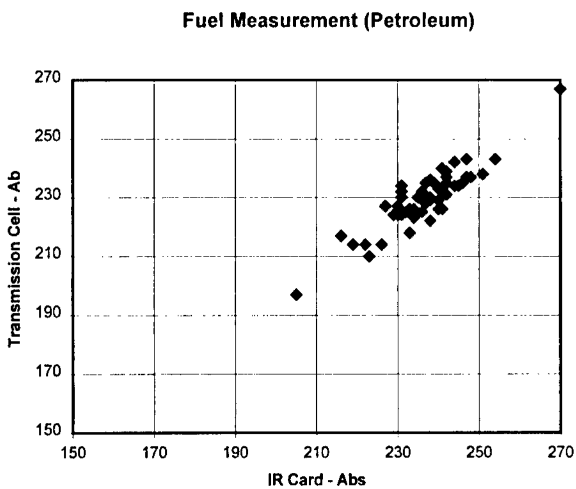

Figure 6: Comparison of Fuel Data
Fuel measurement coefficient of correlation = 0.91

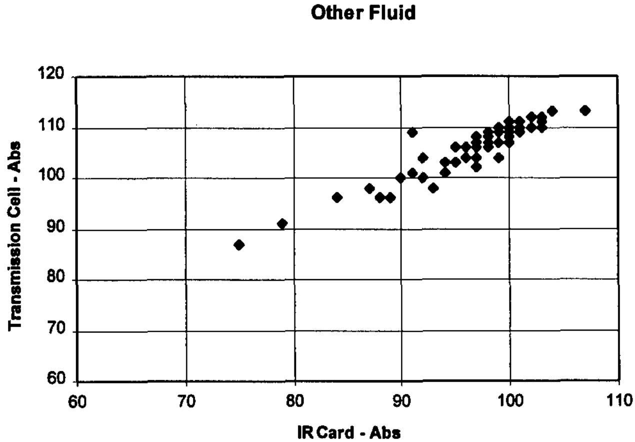

Figure 7: Comparison of "Other Fluid" Data
"Other Fluid" measurement coefficient of correlation = 0.93

Other Fluid: "Other fluid" indicates contamination by an incorrect oil, fuel, etc.

Antiwear results were comparable for the IR card and the cell. There is not an established alarm limit for antiwear in petroleum oils. There were only a few samples with glycol contamination. On these samples, the results were comparable.

Polyol Esters (Mil-L-23699, Mil-L-7808): The study analyzed 190 oil samples from Army air and ground (M1A1) equipment, JOAP-TSC (laboratory prepared) and NAWCAD (laboratory degraded). In general, the IR Card showed a decrease in sensitivity below 1000 cm^{-1} which prevented meaningful readings for antiwear and "other fluid" contamination. To overcome the antiwear problem, a new region is being evaluated for polyol esters. In addition, water contamination in polyol esters cannot be measured using the IR Card. When a water contaminated sample is placed on the Card, the water immediately separates from the polyol ester and rolls to the outer edges of the substrate. Water contaminated Cards were examined microscopically and water droplets could be seen around the outer edges. A possible explanation for this phenomenon is that water is loosely bound to polyol esters (free hydroxyl and single bridge hydrogen bonding [5]) and the oil prefers the substrate to the water. Results are shown in the figures below.

Lubricant Breakdown: There is very good correlation between the cell and card for lubricant breakdown regions (I and II). No discrepancies were noted and there were numerous samples over the limits. (Limits shown are for approximately 1.0 mg KOH/ml and 1.5 mg KOH/ml.)

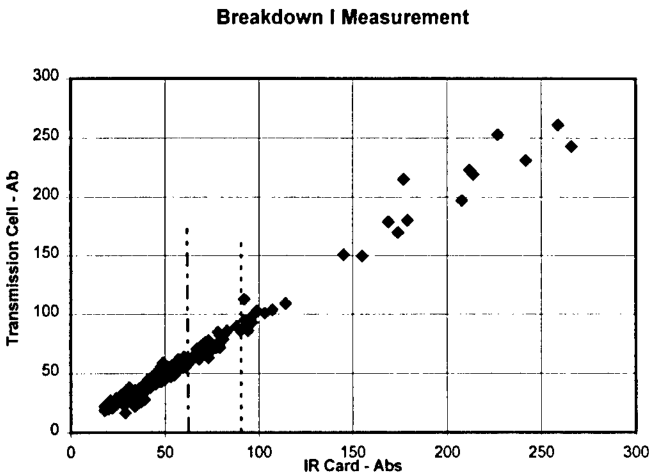

Figure 8: Comparison of Lubricant Breakdown (region I) Data
Breakdown I measurement coefficient of correlation = 0.99

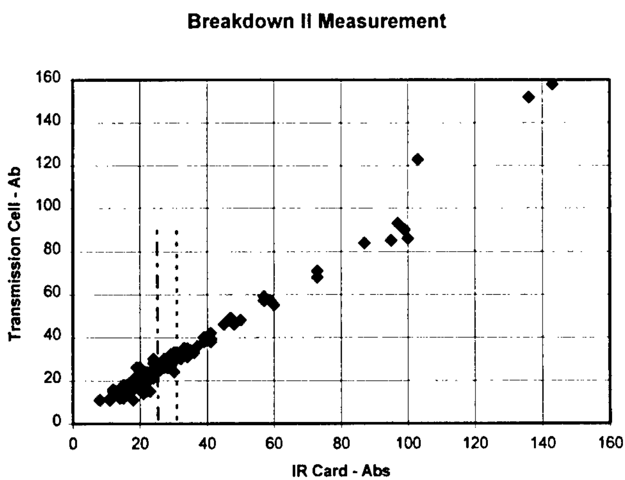

Figure 9: Comparison of Lubricant Breakdown (region II) Data
Breakdown II measurement coefficient of correlation = 0.99

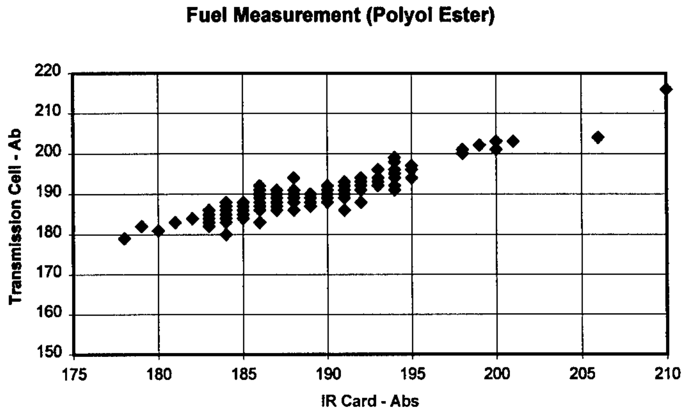

Figure 10: Comparison of Fuel Data
Fuel measurement coefficient of correlation = 0.93

Fuel: There were only a few samples with fuel contamination. Improvements in infrared detection for fuel contamination is ongoing for both the cell and the card.

Conclusions: This study included only 63 petroleum and 190 polyol ester oil samples and as such is insufficient for conclusive findings. However, the results are encouraging, especially for petroleum lubricants. The IR Card will eliminate solvent use, reduce analysis time, virtually eliminate cross contamination and simplify FT-IR operation.

The IR Card manufacturer is researching ways to resolve the polyol ester analysis problems (water and other fluid). In addition, the JOAP-TSC is evaluating a new antiwear measurement area for polyol ester oils.

Acknowledgements: The authors would like to thank Dr. Jay Powell, Bio-Rad, for modifying the FT-IR instrument settings for IR Card analysis. The authors would also like to thank Mr. John Shimski, Naval Air Warfare Center Aircraft Division (NAWCAD), Fuels and Lubricants Division, for supplying the degraded polyol ester lubricant samples.

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The Development of a Predictive Model for Condition-based Maintenance in a Steel Works Hot Strip Mill

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Abstract: A recently developed condition-based maintenance model is described which utilises reliability data combined with condition monitoring measurements to predict the remaining useful life of critical components in a steelworks hot strip mill. The results obtained from several case studies are presented which will show how the model can be used as part of a condition-based maintenance strategy.

Key Words: Condition-based maintenance model; condition monitoring; failure prediction; hot strip mill; life prediction; statistical process control; steel works.

Introduction: In a highly competitive industry, steel works management has to continually focus on achieving increased product performance, quality and efficiency in order to maintain a fair share of the available market and improve its customer base. In an integrated steelworks complex, the hot strip mill is constantly a crucial area of operation in which unscheduled failure or breakdown of machinery can critically affect production down time and associated risk of a reduction in finished goods quality.

For several years, steel companies in the UK have practised condition-based maintenance in strategically vital areas such as the hot strip mill. The methods of monitoring utilised cover virtually the whole spectrum of activity; these include vibration analysis, oil and wear debris analysis, and performance monitoring using numerous techniques to measure, e.g., motor current, temperature, etc.

The present utilisation of these methods enables plant maintenance personnel to detect and also, very often, diagnose pending failure of equipment. What they are unable to do with much certainty is to predict the remaining useful life of failing components.

The predictive model described in this paper has been developed on the assumption that the failure pattern can be divided into two distinct phases: stable and unstable, which can be distinguished by using statistical process control methods. Depending on the way in which the machinery progresses to failure, one of two methods is employed to predict the remaining machine life. The first is based entirely on a reliability model, while the second method uses a novel combination of reliability and condition monitoring measurements to narrow down the time to failure 'window'.

After describing the methodology used to generate the predictive model, the results of several case studies will be presented which will serve to show how it can be utilised as part of a condition-based maintenance strategy on the hot strip mill.

Development of a prediction model theory:
a) Some basic aspects

For the purpose of identifying that a potential failure problem exists in the hot strip mill, normal alarm limits are utilised on which the levels are periodically adjusted based on factors such as: operational experience, machine supplier recommendations, previous failure data, or national/international standards. The problems imposed by reliance on these methods is that if the alarm limits are set too high, the machine may fail without sufficient advanced warning. If the limits are set too low, the machine will generate false alarms that can obscure a true warning until it is too late. Experienced machine operators and maintenance personnel learn from experience how to distinguish between false and true alarms. However, to try and mimic such experience through the development of a model to predict failure is beset by a number of difficulties.

Some of these difficulties may be addressed by employing a statistical process control (SPC) approach which can be utilised to distinguish data in terms of stable or unstable regions by setting suitable alarm limits. This requires the observation of at least 30 data points and from which, the number of false alarms is expected to be reduced. However, this is machine and process dependent and needs to be conducted for each individual situation. It is, therefore, a time-consuming activity which may be alleviated to some extent by comparing measurements for a group of otherwise similar machines, thereby providing a larger population of failures from which to extract data and establish realistic alarm limits.

Cumulative Summation (CuSum) is a well known, sensitive method used to identify small changes in the average value of a data set. It is also a useful technique for smoothing data and enhancing any fundamental changes occurring in the process characteristics. Similar to SPC control limits, a 'v-mask' can be constructed using the CuSum data to identify when a process is getting 'out of control'.

In predicting the remaining useful life of a machine, previously developed models have based their approach on the extensive use of reliability data coupled to a number of simplifying models [1][2][3]. However, although the prediction is seldom precise enough to be useful for predicting the remaining life of individual machinery, they have been found to be useful for optimising maintenance strategies.

A commonly encountered reliability model applied to repairable systems is the Renewal Process. It assumes: i) that when a machine fails, it is repaired perfectly; i.e., 'As good as new', and ii) that times between failure are independent and identically distributed. When these assumptions hold true, the process is said to be *stationary* and a reliability model can be easily constructed. A special case of the Renewal Process is when inter-arrival times are independently and exponentially distributed with a constant failure rate. This is known as the Homogenous Poisson Process. It is known that the probability of some arbitrary number of failures exhibit a Poisson distribution.

However, in practice, the time to failure is generally a function of many variables, including: design, operating conditions, environment, quality of repairs, etc. It follows,

therefore, that failure times are neither independent nor identically distributed and hence, the Renewal Process is very limited in its scope for application in this area.
All the above models use a single distribution function for all the times to failure over the entire life of the system. This will not be the case, since changes due to deterioration or improvement cannot be modelled by a single distribution function [4]. Hence, a stochastic point process for a repairable system would seem to be a more appropriate approach to adopt.
Christer and Waller [1] present a general methodology for modelling planned maintenance in which they introduce the concept of delay time analysis to model failure detection such that the time period is estimated from when a fault is detected to the point of ultimate failure. However, they found that reliability data was unsuited to this approach and a questionnaire was used in conjunction with human (i.e., the manager's) judgement in order to successfully optimise the preventive maintenance system at that particular location.
Weibull analysis has proved to be a powerful tool in establishing reliability - based diagnosis, from which distinctions can be drawn between infant mortality, random failure and wear-out conditions of machinery. Using reliability data to predict the performance of the machine generally involves assuming that the historical performance will reflect the current performance. The latter is best measured by strategic use of machinery health monitoring techniques. Therefore, the best way to utilise this information to predict failures is by intelligent use of predetermined alarm limits. An example of the kind of approach that can be adopted comes from the aerospace industry where so much of the leading edge maintenance technology has been developed in recent years. Initially, a deterministic model was derived, but it proved to be ineffective for indicating whether an engine should be overhauled or left in service. Sarma et al [5] derived a stochastic model which incorporated sample and noise measurement. This new model proved more successful in identifying problems and formed the basis of a decision process that indicated whether an engine should remain in operation. More recently, Pulkkien [6], developed a mathematical model of wear prediction in conjunction with monitoring the condition of a single component.
A proportional hazard model has been developed, by Knapp and Wang [7], which predicts the remaining time to failure of a machine. It uses a baseline hazard rate, stated as a function of time, and a hazard function based on the machine condition variables. Upon determining the hazard rate, the reliability of the machine is estimated over the subsequent time period from the current sample point.
From the above description of some relevant developments, it is evident that two models are required: one to describe how the component deteriorates; the other to relate the degree of deterioration in the 'condition' of the equipment being monitored.

b) Prediction model theory

The first part of the model relates to ensuring the earliest identification of a problem. From analysis of numerous failure data on the hot strip mill, a general failure pattern becomes apparent which takes the form shown in Figure 1.

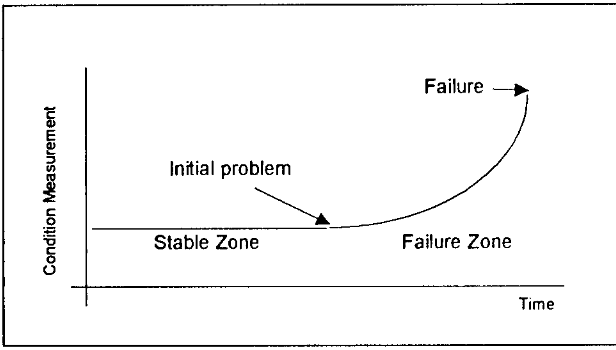

Figure 1: General Failure Pattern

In the 'stable zone', measurements are simply varying about an average value. The variance may be due to process changes between successive measurements and/or measurement error. When the measurements start to deviate from these values, it becomes apparent that a problem exists and the machine may have entered the 'failure zone'. The setting of realistic alarm limits is achieved using SPC theory, such that when the condition monitoring measurements move outside the limits imposed, (normally set at three standard deviations about the average) the condition is registered as being 'unstable' and the operation has entered the designated failure zone.

'Remaining life' models based solely on reliability theory are related to time-based estimates from a new (or repaired) machine condition. If the measurement of a machine's condition is now included, the overall failure time is estimated in terms of detection (reliability) and failure prediction (reliability plus condition monitoring).

In quantifiable terms, by using a Weibull distribution function, we obtain:

For the stable zone:

$$TTF = c_1\left[-ln\{1 - F(t)\}\right]^{\frac{1}{m1}} + c_2\left[-ln\{1 - F(t)\}\right]^{\frac{1}{m2}} - t \tag{1}$$

For the failure zone:

$$TTF = c_2\left[-ln\{1 - F(t)\}\right]^{\frac{1}{m2}} - t2 \tag{2}$$

Each zone is defined in terms of whether the condition monitoring measurement is inside or outside the alarm limits.

On this basis, it is evident that the 'condition' data acts as 'switch' or 'go/no go' signal in moving from equation 1 to equation 2. However, in order to make further use of the condition data, a model of the failure zone pattern is also introduced. This is depicted in Figure 2.

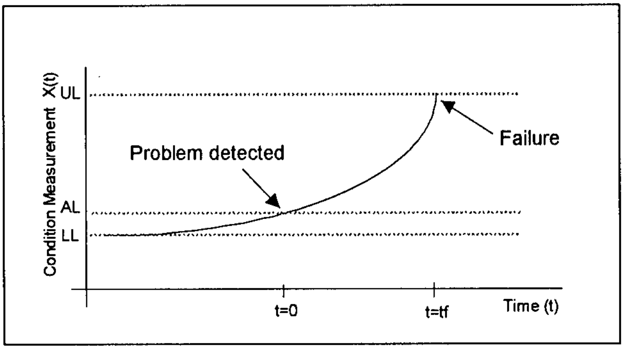

Figure 2: Failure Zone Model

The failure condition commences at the lower limit (LL), which is the averaged conditional value within the stable zone. The condition measurement (X(t)) increases until it is detected passing through the alarm limit (AL). Subsequently, at some time, t =tf, the upper limit is reached (UL) and the machine needs to be inspected or withdrawn from service.

Inspection of actual failure case histories revealed that the failure pattern could be approximated to an exponential curve. While this behaviour cannot be said to apply to every situation, it nevertheless serves as an initial starting point for developing the prediction model. Later, a wider spectrum of failure pattern will be introduced and the model will be adjusted accordingly.

Proceeding on this basis, the failure zone is expressed as :

$$X(t) = LL + (AL - LL)\exp^{\frac{\ln\left[\frac{UL-LL}{AL-LL}\right]}{tf}\times t} \tag{3}$$

Values for LL and AL are obtained from the SPC modelling of the stable zone. The estimate of UL is more problematical since it is the maximum possible level the machine is permitted to reach before actual failure occurs. UL must, therefore, be estimated using appropriate information available either from within the company, or from outside sources, such as equipment suppliers, or by reference to universal standards. The time 'tf' is obtained by reference to reliability analysis of previous 'failures', and is, therefore, obtained directly from Equation 2. By rearranging Equation 3, an expression for 't' is obtained with respect to the measured condition of the machine.

Hence, the remaining life, after entering the failure zone, is

$$TTF = tf - t \tag{4}$$

By further substituting the values of 't' and 'tf', we obtain:

$$TTF = c_2 \left[-ln\{1 - F(t)\} \right]^{\frac{1}{m2}} \times \left[1 - \frac{\ln\left[\frac{X(t)-LL}{AL-LL}\right]}{\ln\left[\frac{UL-LL}{AL-LL}\right]} \right] \qquad (5)$$

To summarise: in order to predict the remaining life of the machine, Equation 1 is used while the condition monitoring measurements lie within the pre-set alarm limits; i.e., in the stable zone. When the condition monitoring measurements indicate that a problem has occurred, i.e., entered the failure zone, Equation 5 is utilised, in which the time to failure is predicted using a combination of reliability and condition monitoring measurements.
To best illustrate the way in which the model is designed to function a computer program was written to simulate typical machine failure patterns of the type observed to occur frequently in the hot strip mill. The simulated machine failure pattern comprised a stable zone of, on average, 20 weeks duration, followed by a failure zone which was also an average of 20 weeks. The effect on the prediction of varying the time was also assessed, and Figures 3, 4 & 5 show the results obtained for three different conditions. In Figure 3, an ideal failure pattern is demonstrated. In the stable zone, a wide distribution is obtained which reflects the uncertainty which accompanies sole dependence on reliability data. In the failure zone, the prediction rapidly becomes much more narrow and focused, eventually identifying the failure time as being 40 weeks from start with a very high certainty, depicted by the increased 'sharpness' of the distribution peak. The nearer the time approaches the actual failure time, the more certain is the prediction.

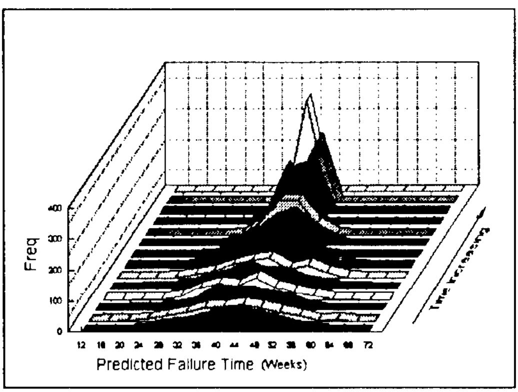

Figure 3: Illustrating an ideal failure pattern at 40 weeks

In Figure 4, the machine experiences a much shorter failure zone of 10 weeks, in which it is evident that the model 'tracks' the time to failure (~ 30 weeks) as the later condition monitoring measurements are also used.

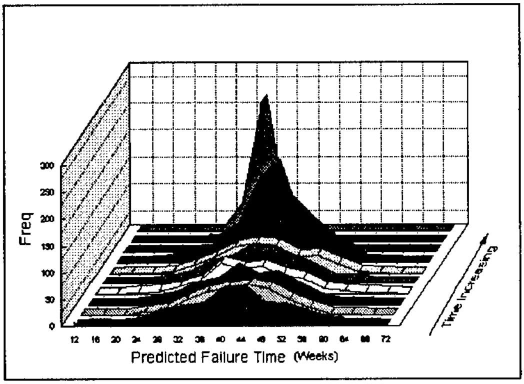

Figure 4: Illustrating a shorter failure zone, failure at 30 weeks

If the stable zone time also deviates from the ideal average time, a 'step' jump is observed to occur in the prediction distributions, as is demonstrated in Figure 5 in which the stable zone only lasts for a period of 10 weeks. Once again, in the failure zone, the model tracks to the point of failure after 50 weeks.

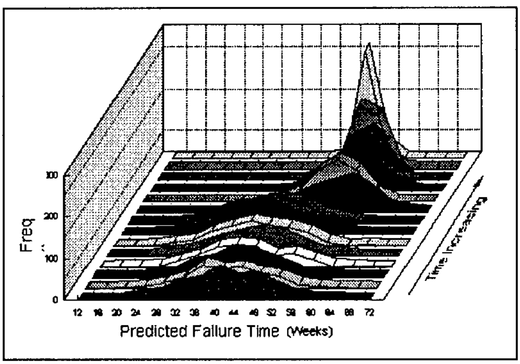

Figure 5: Illustrating a longer stable zone time, failure at 50 weeks

Case Studies: A number of hydraulic pumps located on the hot strip mill, and subjected to regular condition monitoring using vibration analysis, were selected for an initial case study.

The present condition monitoring methods and strategies used on the mill are generally very effective in identifying pumps which require attention before a catastrophic failure occurs. However, no method currently exists for predicting the remaining useful life of the pumps while they are still in operation. The condition monitoring data used in this study is based solely on the measurement of overall vibration level.

The machine group selected for the initial assessment comprised three double vane pumps. Each delivering 320 litres per minute of hydraulic fluid at 160 Bar pressure. The pumps are each driven by a 120 kW electric motor at 1485 rev/min. The system supplies the

hydraulic requirements to critical machinery, including the Reversing Rougher, Vertical and Horizontal Scale Breakers.
SPC analysis of the stable measurements resulted in an average condition measurement value of 6 mm/s and an estimated alarm level of 9.5mm/s. Subsequent Weibull analysis revealed that the distribution approximates to a normal distribution with an average stable region time of 260 days. The general failure pattern approximated well to an exponential curve and, as a result, the upper limit was set at 18mm/s. The resulting time from first detection to reaching the upper limit of 18mm/s was averaged out at 104 days. The distributions for all three pumps are presented in Figures 6, 7 & 8. For pump No.1, the condition monitoring measurements only provided sufficient warning to prevent catastrophic failure, although the last measurement taken did pin-point correctly the failure time.

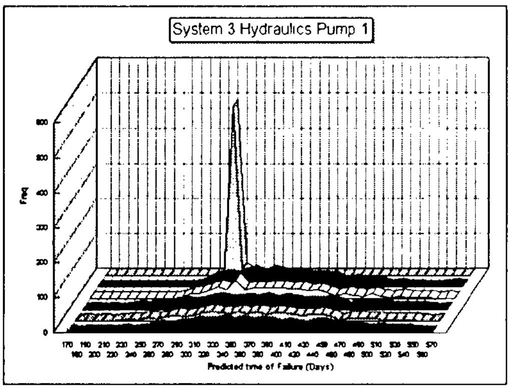

Figure 6: Showing Pump 1 failure predictions

In the case of Pump No.2, there was sufficient data available to provide a more focused prediction of time to failure.

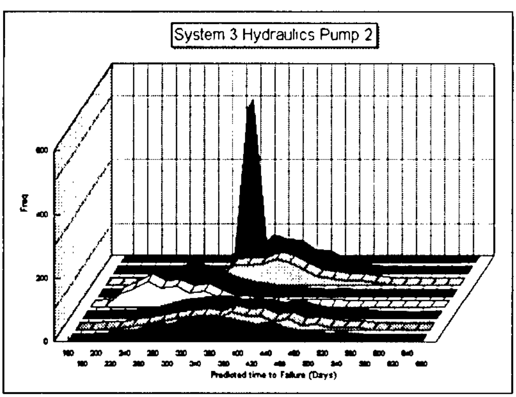

Figure 7: Showing Pump 2 failure predictions

Pump No. 3 failed with a relatively clear failure pattern which is reflected in an accurate prediction to time to failure from an early stage.

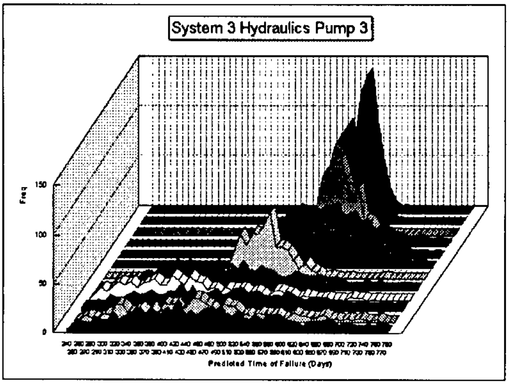

Figure 8: Showing Pump 3 failure predictions

Regarding the matter of deciding the alarm limits; initially, all three methods for detecting a machine problem were used. In the stable region, the measurements were well within the normal alarm limits, but when the measurements were closer to these limits, quite a large number of false alarms were observed; accounting for about 10% of the total number of measurements. By changing to the limits set using SPC, the number reduced to 5%. Using CuSum analysis resulted in a further improvement to only 2.5% false alarms. However, in the failure zone, the CUSum method led to large variation in the measurements which made it difficult to estimate properly the average level and associated distribution. CuSum was, therefore, judged to be best utilised in identifying when the machine problem first occurred. SPC analysis in this zone maintained the level of false alarms, but at the expense of reduced reaction time to failure. Using the normal limits still resulted in a higher percentage of false alarms but it indicated a failure slightly sooner than the SPC analysis.

Conclusions: Currently in industry, condition monitoring can identify when machine problems are occurring and, given enough experience, pin point the exact cause. However, it is more difficult to predict the remaining life of the machine once the problem has been identified and therefore when to change or maintain the machine.
Current literature on remaining life prediction has focused on solely reliability based or mathematically complex models. There is clearly a need for a simple, systematic prediction model readily applicable to the industrial situation.
This paper has attempted to introduced such a model. Condition monitored measurements have been divided into two regions; a stable and failure zone. Whilst in the stable zone, condition measurements are normal and hence a reliability based model is utilised. When condition measurements increase, indicating a potential problem, reliability and condition monitoring information is used to form the remaining machine life prediction.

A case study was carried out to test the model. Initial results were encouraging with all machine failures being predicted before they failed. It was evident that the prediction model was dependent on the quality and accuracy of the condition monitored measurements.
It is anticipated the model will be applicable to most condition monitored situations provided that the failure lead time is sufficiently long and the condition monitoring reflects the health of the machine.

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Condition Based Maintenance in the Pharmaceutical Products Industry
Some Cost Related Benefits

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Abstract: At the 1996 Technology Showcase Conference, a method for assessing the cost effectiveness of condition based maintenance (CBM) was presented for the case of a batch process plant pump operation utilising a simple mathematical model. More recently, the model has been extended to permit evaluation of fans and also gearboxes which attract consequential costs due to there being no stand-by facilities when failure occurs. In this paper, the results of a study are presented and discussed as a means for determining the extent to which the cost prediction model can be utilised to establish the viability of pursuing a condition based maintenance strategy for batch type process plant machinery operation.

Keywords: Batch process plant; condition based maintenance; condition monitoring; cost benefit analysis; fans; gearboxes.

Introduction: Condition monitoring, as an aid to targeting maintenance effort has long been recognised as potentially cost effective. Consequently, condition based maintenance (CBM) has been advocated by some as **the** answer to reducing maintenance costs to an acceptable level in today's highly competitive industrial society. However, the economic arguments have tended to be based primarily on cost analyses which were based on continuously running, high power, high capital cost plant. In fact, there are large sections of industry which function in a batch process environment, in which the economic factors are more difficult to determine and sustain. Nevertheless, if the population of machines is sufficiently large, an economic case may be possible for the successful utilisation of CBM.

In the 1966 Technology Showcase Conference, a simple mathematical model for assessing the cost effectiveness of CBM in batch process plant was presented for the case of pumps in which no consequential costs were involved because of there being stand-by facilities available in case of pump failure (1). The model has subsequently been extended to accommodate the effect of consequential costs which are incurred, for instance, when fans fail (2). Also, the effects of the probability of detection of the onset of failure using CBM and machinery reliability have been incorporated into the revised model.

In this paper, the results of a recent study involving gearbox performance and maintenance are presented, in which the cost savings associated with direct repair costs are related to the capital cost of the equipment by means of a non-dimensional factor (K_d), and the savings in consequential costs by a separate cost factor (K_c), both of which are related directly to the input power of the machines.

Maintenance strategy for gearboxes: The maintenance of gearboxes in the plant require a different strategy to that employed, for example, with pumps and fans. The reason for this becomes self-evident in the light of consequential costs associated with their failure, as illustrated in Fig.1, which is based on the analysis of a range of individual gearboxes located on plant. It also reveals that the costs incurred is not a **direct function of** the power transmitted.

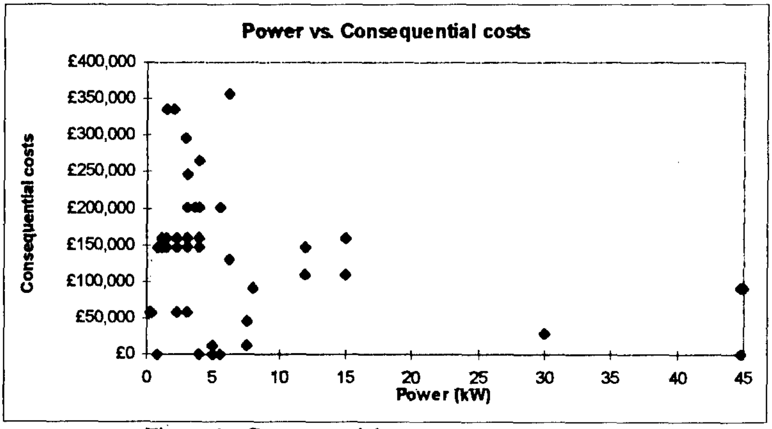

Figure 1 - Consequential costs versus power

Direct duplication or provision of 'On-the-shelf' spares will not remedy the situation in the majority of cases since the gearboxes are located on reactor vessels and dryers in which their failure leads to the production batch being lost due to the reaction being effectively out of control. To deal with this type of situation requires that the systems used must be 'fault tolerant'; i.e., the gearboxes are grossly over-designed for the particular duty so that even if a failure condition develops, the gearbox will continue to function until a 'time-window' can be found to carry out the necessary repairs. The few occasions where gear tooth failures have occurred are associated with phosphor-bronze worm-wheel type reduction gearboxes in which considerable wear and misalignment can be tolerated before complete failure occurs.

The use of condition monitoring techniques has to be considered very carefully for gearboxes operating under these conditions. Higher power gearboxes (>150 kW) are routinely monitored using oil analysis. This is done primarily to sentence the oil rather than detect incipient failure. Vibration analysis is utilised with gearboxes which attract high direct repair costs simply to minimise the damage within the box before repairs are effected.

To summarise: Whereas, in the main, consequential costs are minimised by over engineering the product, there is a price to be paid in a much higher level of capital cost incurred.

Analysis of direct and consequential costs: This analysis is based on a sample of 87 gearboxes across the plant. The total population of gearboxes is 398. Over a 5 year period there were 74 failures of these gearboxes and hence,

Failure rate $\lambda = \dfrac{74}{5 \times 87} = 0.17$

and, assuming that the failure distribution is Poisson,

Reliability $R_t = e^{-\lambda} = e^{(0.17)} = 0.844$ (1)

Direct costs of gearbox failure were acquired using the same method as for fans and pumps. These have been analysed using the same model as for fans and pumps i.e.

$C_d = C_c \bullet I_p \bullet I_c \bullet I_{pr} \bullet K_d$

where, C_d = Direct repair costs

C_c = Capital cost of gearbox

I_p = Power index

I_c = Criticality index

I_{pr} = Process index

K_d = Direct costs factor

The relationship between K_d and power was found to be of the form:

$y = 34.54 \bullet e^{-0.0053x}$ (2)

In terms of the relationship between repair costs and power, there is considerable scatter below 50 kW, nevertheless, a linear fit is obtained of the form:

$y = 24.60x + 1018$ (3)

With regard to consequential costs the relationship is of the form:

$C_q = C_c \bullet I_p \bullet I_c \bullet I_{pr} \bullet K_c$

where, C_q = Consequential costs

K_c = Consequential costs factor

Again, from inspection of the data it was evident that there was considerable scatter and that it was better to divide the data into two distinct power ranges, $\leq$ 15 kW and >15 kW, as shown in Figures 2 and 3, respectively.

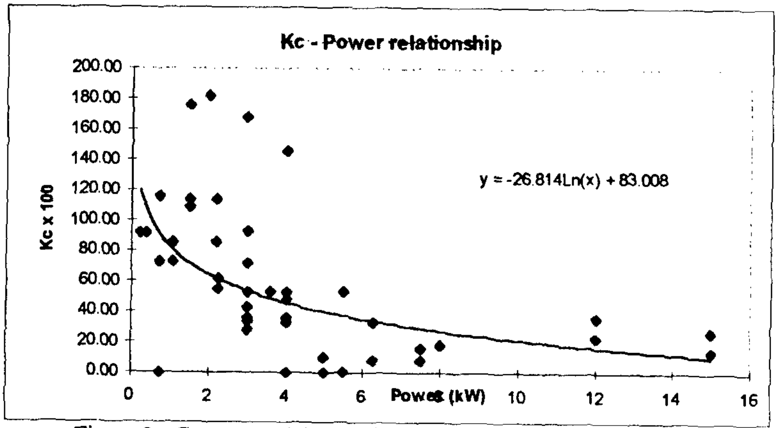

Figure 2 - Consequential costs factor, K_c versus Power (< 15 kW)

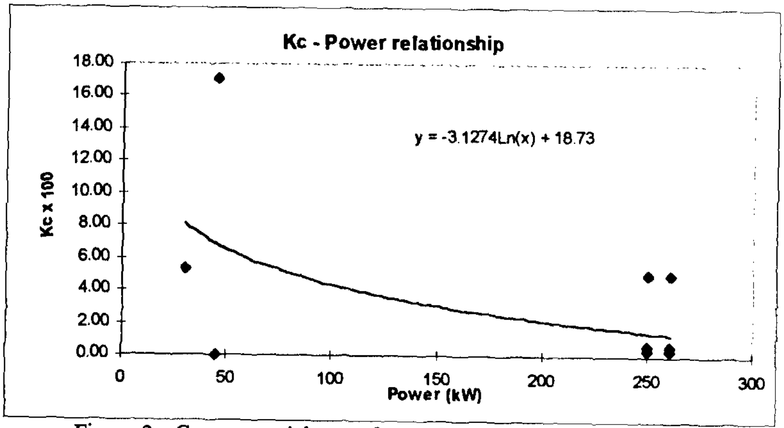

Figure 3 - Consequential costs factor, K_c versus Power (>15 kW)

Testing the model: Three gearboxes, which had not been included in the study, were selected and their direct and consequential costs ascertained and compared with those predicted using the above relationships. The gearbox details are presented in Table 1 below.

Table 1 - Gearbox details

Class of Machine	Machine Description	Corrected Cost*	Direct Costs*	Consequential Costs*	Power Index	Criticality Index	Process Index
Gearbox	Gbox 'A'	£2,442	£222	£159,512	1	10	9
Gearbox	Gbox 'B'	£3,519	£1,852	£45,530	2	10	4
Gearbox	Gbox 'C'	£5,345	£1,652	£28,542	5	10	2

(*) These figures are in pounds sterling, as is also the case in Tables 2 and 3 below.

The formulae tested were:

1) Direct costs as predicted by $K_d = 34.541e^{-0.0063(Power)}$ and $C_d = C_c * I_p * I_c * I_{pr} * K_d$

2) Direct costs as predicted by $C_d = 24.595(Power) + 1017.9$

3) Consequential costs as predicted by $K_c = 83.008 - 26.814Ln(Power)$

(For gearboxes with input power <15 kW)

$K_c = 18.73 - 3.1274Ln(Power)$

(For gearboxes with input power >15 kW)

The results based on the predictions are listed in Tables 2 and 3 below:

Table 2 - Direct costs

Machine description	Predicted direct costs (1)	Predicted direct costs (2)	% difference (1)	% difference (2)
Gearbox 'A'	754	1,045	240	370
Gearbox 'B'	927	1,202	-50	-35
Gearbox 'C'	1,528	1,756	-7.5	6.2

Table 3 - Consequential costs

Machine description	Predicted Consequential costs	% difference
Gearbox 'A'	176,845	11
Gearbox 'B'	81,578	79
Gearbox 'C'	43,260	52

Clearly, the agreement at low powers is not good, but improves considerably at higher powers.

Concluding remarks: The purpose in developing the model is to provide management and engineers on plant with appropriate means to decide whether the employment of condition monitoring methods as part of a condition based maintenance strategy is a viable prospect. It is evident that a simple mathematical model can be used to predict the direct and consequential costs of machinery failure with a reasonable degree of confidence., although it is also apparent that some refinements are necessary to improve the prediction, especially for lower power units. By using the results it is possible to set up a decision making system to evaluate the cost effectiveness of different maintenance regimes, along similar lines to the method described in references (1) and (2). As was found in the previous analyses of pumps and fans, an essential element of the decision making process is the reliability of the machinery class involved and the probability of detection using machinery health monitoring techniques. Consequential costs outweigh all other considerations and, therefore, some form of condition based maintenance is the most effective way of dealing with the problem.

Acknowledgements: The authors wish to acknowledge with grateful thanks the kind permission of Glaxo Wellcome Operations, International Actives Supply, to present and publish this paper.

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Counting the Cost of Machinery Health Monitoring in the Steel Industry

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Abstract: A model developed originally at Glaxo Wellcome Operations, U.K. Ltd., by B.S.Rajan has been adapted and modified in order to assess its suitability for application in the steel industry; exemplified typically by the maintenance requirements of the Hot Rolling Mill. Several models were investigated and evaluated, from which, Rajan's model was selected. The direct repair cost and consequential cost savings are established and examined in relation to the cost of carrying out machinery condition monitoring. A sensitivity test was undertaken to identify the most critical factors which control costs. These were found to be: probability of detection of machine deterioration, machine reliability, standby facility, system downtime duration, and the efficiency of condition monitoring utilisation.

Keywords: Condition monitoring, economic justification, cost benefit, maintenance, management tool

Introduction: Condition monitoring plays an increasingly important part in modern maintenance practice. However, there are some unfavourable aspects which have hindered the progress in ensuring that such methods are utilised to the very best advantage and are, therefore, fully cost beneficial. Some of these issues are summarised as follows:

- under -utilisation of plant machines
- too few machines in use to permit adequate experience
- operators continuing to place too much reliance on their own senses
- highly mobile equipment

It is not surprising, therefore to find it difficult to make the decision whether to use condition monitoring, and if so, which techniques to use. An early programme designed to assist industry in grappling with these issues was initiated in the U.K. by the Department of Trade and Industry. M.J.Neale and Associates were commissioned to conduct a survey which was published in 1979 [1]. In 1986, Rao [2] published details of a model which was designed to enable better use of failure and repair cost data. A method for justifying the use of condition monitoring methods in maintenance is in use by the Management Consultants, Moret Ernst and Young in the Netherlands, [3], in which the cost of using condition monitoring is compared against the cost of the alternative technologies, such as Time-Based Maintenance(TBM), or eliminating the consequential cost of a breakdown, etc. However, the model adopted for this study is based on that developed originally by Rajan [4]. This approach was adopted because it is based on a group of similar machines and hence, increases the probability of obtaining real cost savings, thus making it easier to justify the cost of employing condition monitoring methods.

This development was undertaken in the first instance to deal with batch process situations of the type experienced in the pharmaceutical products industry. The first step was to develop the model for pumps with standby facilities, in which it can be reasonably assumed that there will be no consequential costs due to failure.

Subsequently, the model was refined to take account of consequential costs and then was applied to examine instances where there were no standby facilities, such fans,[5] and also, gearbox installations [6].

The purpose of this investigation, therefore, was to establish whether the same model, or some variant of it, can be utilised for assessing the cost benefits of using condition monitoring in an entirely different industry, such as, e.g., the steel industry. This paper, therefore sets out to describe the way in which the original model was first adapted and then used to obtain some initial results of analysis for a hydraulics system situated in the hot rolling mill.

Development of the revised model: The essence of the model is a comparison of possible maintenance budget savings by comparing breakdown maintenance with the running costs of condition-based maintenance. The savings possible take into account both the direct and consequential costs of failure and the model is presented in the form of simple equations in conjunction with a MS Excel spreadsheet. The equations used for the cost comparisons differ for each group of machines under consideration but the basis of the comparison remain the same. Commencing with Rajan's cost model developed for pumps in which only the direct costs were involved, the predicted pump condition monitoring savings are:

$$Cs = 0.8\,[D]^*\,[\textit{unreliability}]^*[Rc] - [\text{CBM cost}] \qquad (1)$$

Where: Rc = direct costs of failure

CBM = condition-based maintenance

and reliability is determined by consideration of the Mean Time Between Failure in a Poisson-based failure distribution

The factor 0.8 is a factor to allow for the money that can be saved through the application of CBM instead of Breakdown Maintenance (BDM).

In addition, because no condition monitoring programme is capable of detecting all failures, a factor, 0.75, is introduced to represent the savings possible from using either high or low level monitoring systems - denoted as D, which is determined using the procedure outlined in reference 4.

The predicted repair cost is represented by the equation:

$$Rc = Cc^*Ip^*Ic^*Ipr^*Kd \qquad (2)$$

where: Cc = capital cost of machinery

Ip = power index

Ic = criticality index

Ipr = process index

Kd = direct cost factor

For further details of the development of equation 2, see reference 4. However, examination of the hot strip mill operating condition revealed that the equation required to be changed, leading to:

$$Rc = Cc^*Ip^*Ic^*Kd \qquad (3)$$

Equation 1 also includes the running costs of monitoring the condition of the pumps. and they can be sub-divided into variable and constant costs. The former are the hours required for measurement and analysis of the condition monitoring data (T), multiplied by the hourly labour costs, (L). The latter costs are those which account for the capital cost of the monitoring equipment, (VI) divided by the amortisation period and taking into account the number of items(pumps, say) - (N). The amortisation period represents, therefore, the total number of years the equipment can be effectively utilised before it is totally incapable of further use.
Hence, we have:

$$C = T*L + \left\{\frac{VI}{amortisation*N}\right\} \tag{4}$$

The decision whether to utilise condition monitoring is made by reference to the costs of performing condition monitoring when compared with the predicted savings based on the criterion: $N*[\textit{pay-back period}] > \frac{VI}{Cs}$

For situations in which there is no standby facility, Rajan's equation 1 now becomes:

$$Cs = 0.8*[D]*[\textit{unreliability}]*[Rc] + [D]*[\textit{unreliability}]Rq - [\text{CBM cost}] \tag{5}$$

Where: Rq = consequential costs of failure = Ip*Ipr*Ic*Kc
Kc = consequential cost factor

Utilising the above equations leads to the determination of the number of machines required in a given group to make CBM viable. This approach is based on the expectation that similar savings can be achieved within a group of identical machines, and that 'small' savings can add up sufficiently to justify the use of CBM on a 'self-fundable' basis.
In the case of a hot rolling mill of an integrated steelworks, it requires that a group of identical or similar machine types be identified that are, nevertheless, critical as regards to their effect on the efficiency and availability of the mill operation if they should fail with consequential mill down-time implications.
A representative example of such a group is the deployment of hydraulic pumps. Some of these locations have multiple pump installations operating with a single standby pump. Based on Rajan's results [4], the equation for Kd is given by:

$$Kd = (74.58.\ 10^{-4})*\ e^{(-0.009*POWER)} \tag{6}$$

For the hot strip mill, the possibility of consequential costs has to be allowed for in which the costs of a failure are counted in terms of downtime and product loss. The costs incurred through downtime on the mill can vary by an order of magnitude from as little as $1500 per minute. The consequential costs of the loss of product may be assumed to have an average constant value. The other consequential cost implication relates to the effect of standby facility failure, and hence, the probability of detection of machine deterioration, D is taken into consideration. This is combined with the consequential cost probability on the assumption that a stand-by pump does not fail before being activated, and hence condition monitored.

Therefore, based on this premise:

$$\text{System Failure Cost} = (D^* [1-R(t)]^{(\text{standby}+1)})^* \{\textit{downtime}^* X + Y\} \qquad (7)$$

where: R(t) = Reliability
X = Downtime cost per minute
Y = Product value

and hence, $Rq = \dfrac{\text{System Failure Cost}}{\text{Standby} + 1}$

Further rationalisation and refinement of the above requirements through analysis of the mill operationg condition, leads to the final set of equations as follows:

$$Cs = 0.8^*D^*[1-R(t)]^*Rc + Rq - \text{CBM costs} \qquad (8)$$

$$Rc = Cc^*Ip^*Ic^*Kd \qquad (9)$$

$$Rq = \frac{(D^*[1-R(t)]^{(\text{standby}+1)} * \{(\text{Down-time} * X) + Y\}}{\text{standby} + 1} \qquad (10)$$

$$\text{CBM cost} = L^*T + \frac{VI^*(bi)^{pb} * T}{pb^*TT^*U} \qquad (11)$$

where: bi = base rate of interest
pb = pay-back period (years)
TT = total time available for equipment utilisation
U = degree of equipment utilisation (%)

Note: These equations are only applicable for the hydraulic pump systems and are expressed in terms of the savings per machine.

Results: The revised model was used to analyse several hydraulic pump systems operating in the hot rolling mill and which were selected initially on the basis that the information required was available. Even so, using this approach still posed a number of problems in obtaining all the information required. For this reason, a sensitivity test was instituted so that the effect of any variations or uncertainties in applying the data could be tested and evaluated. The results presented here are representative of a considerable amount of analysis undertaken to establish the effects of these variables on the cost prediction capability of the model.

Among the variables that may influence the decisions to be taken, the following were considered to be of particular relevance and interest:

- Possible savings ratio between BDM and CBM repair cost
- Probability of machinery deterioration detection
- Reliability of machinery
- Average system downtime
- Time available for condition monitoring equipment usage

Varying the savings ratio from the notional value of 0.8 (the same value used by Rajan, [4]) up to 1.25 shows that for an increase of 56%, there is only an increase in savings here of just over 2%. This is a direct result of the high consequential costs of system failure. The probability of detection 'norm' achieved by using condition monitoring

is 0.75. A variation in this value from 0.6 to 0.85 reveals that it has significant influence on the outcome, as demonstrated by Figure 1, in which there is a fluctuation in savings of -39% to +31% within this range. If the range is expanded from 0.1 to 0.95 confirms that it is a highly non-linear characteristic. A detection in machinery deterioration above 50% appears to signal when condition monitoring really begins to take effect.

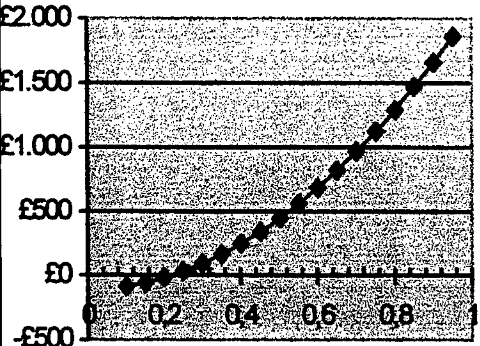

Figure 1 Variation in deterioration factor

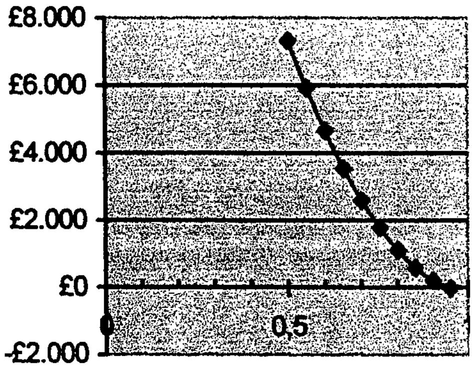

Figure 2 Variation in reliability

Past results have shown that the reliability of hydraulic pumps is approximately 80% for the hot strip mill. Figure 2 shows that by varying the reliability from 50 to 95 %, has considerable impact on the savings possible in which it becomes much harder to justify the cost of condition monitoring as the reliability improves above about 75%. This demonstrates the importance of achieving a correct definition of failure.
The impact of machine downtime costs is of particular interest, as shown by the results of a sensitivity test plotted in Figure 3, in which the range of interest: from as little as 1,500 to as much as 15,000 US dollars per minute reveals a linear response. [Note that the vertical axis of Figure 3 is scaled in pounds Sterling]. When the downtime cost falls below about $3,000 per minute, the case for using condition monitoring begins to become harder to justify. A clear identification of the downtime costs per minute is, therefore, essential. For the case where the downtime cost is $15,000 per minute, the results of a comparison between the variables under consideration and the condition monitoring savings per machine is summarised in Table 1 below. More detailed information is to be found in reference 7.

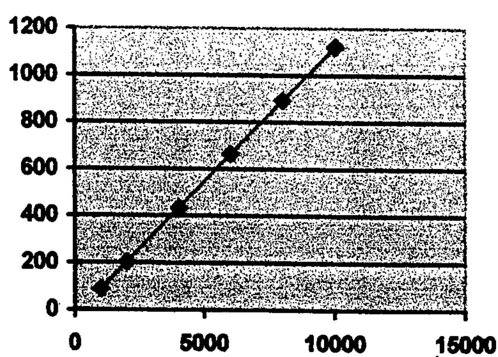

Figure 3 Influence of downtime cost

Table 1 The effect of process variables on cost savings

VARIABLE	SAVINGS PER MACHINE		
		Sensitivity	
	Hardly	Very	Extremely
Savings factor between CBM and BDM	√		
Probability of deterioration detection		√	
Machine reliability		√	
Repair cost prediction inaccuracy	√		
Machine type assessed (cost + power)	√		
Stand-by facilities			√
Equipment purchase cost	√		
Pay-back period	√		
Labour cost per hour	√		
Time required per year for con. mon.	√		
Degree of equipment utilisation			√

Conclusions: Certain parameters influence the justification of condition-based maintenance more than others. For the case of the hydraulic pumps sited on the hot rolling mill of an integrated steelworks, the operations are very sensitive to:

- Probability of deterioration detection
- Machine reliability
- Number of stand-by facilities
- Degree of condition monitoring equipment utilisation
- System failure downtime duration

The model can be utilised in the first instance as a means of convincing company management the extent to which condition-based maintenance can be employed with a reasonable expectation of achieving realistic savings.
Ultimately, the most important utilisation of the model will be its use in conjunction with the prediction of remaining useful life of equipment and hence, strategically where best to deploy condition monitoring facilities and manpower.

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On the Relation Between Operating Conditions and Changes in Vibration Signature: A Case Study in Paper Mill

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Abstract: To achieve effective diagnosis and prognosis, relevant and reliable data from the surroundings are required in addition to the vibration measurements. The paper classifies stoppage times and highlights the reasons behind them. Also, it discusses the consequential economic losses incurred by unplanned stoppages. Further, it presents a new approach to envelope alarming, which is called dynamic alarm. It is applicable to identical bearings and those of approximately identical vibration signatures. One of the important conclusions from this study is that it is not only the variation in the machine loading which affects the amplitudes of the bearing defect frequencies, but also the machine speed does. Therefore, changes in the machine speed and load should be considered when interpreting vibration spectra. This will improve the effectiveness of vibration diagnosis and prediction of the time to replacement. During the period covered by this study, which is fifty eight days, it was found that the total stoppage time due to unknown reasons was very large and caused appreciable economic losses of about 2,3 millions SEK. The dynamic alarm is shown theoretically to offer later renewal with fewer failures, and therefore lower cost and higher productivity.

Key Words: Operating conditions, unplanned stoppages, dynamic alarm, vibration monitoring, diagnosis.

Introduction: The vibration spectrum consists of many frequencies of different amplitudes. These frequencies are usually generated by failure causes such as imbalance, misalignment, damage in rolling element bearings or in gear boxes, natural frequencies of the machine parts, etc. [1]. Identification of these frequencies leads to identify the basic causes behind deterioration while damage severity is usually assessed by the amplitude of the considered frequency(s) or frequency band(s). But, the vibration signature is usually changed due to the effect of many factors especially machine operating conditions such as load and speed. Acquisition of better data coverage and quality, which describe these factors in addition to the vibration measurements, eases the task of the maintenance engineer to perform effective diagnosis and prognosis. Frequencies are specific to the bearing but the surrounding structure damps some more than others and occasionally may resonate. The structure responds to the actual frequencies so if machine rotational speed and/or load changes the response spectrum may be quite different. Bearing defect vibration frequencies usually deviate from their theoretical values according to many factors such as faulty installation and operating conditions. These deviations should be considered when interpreting bearing vibration spectra because frequency shift confuses the analyst [2,3]. Therefore, it is important to keep numerate records of the operating conditions such as

machine load, speed and operating temperature to distinguish and confirm the reasons behind changes in the vibration signature. In this paper, data and information concern stoppage categories and times, causes behind these stoppages and total stoppage time gathered from a Swedish paper company are presented. The analysis and results of these data are discussed. The concept of the dynamic alarm is presented and explained by an example which is followed by conclusions.

Data Gathering: The paper mill company under study has 4 paper mill machines of different ages. One paper machine, called PM1, was selected for investigation because its database includes more replacements of identical bearings than the other machines' databases. Data from the production and maintenance departments during two months are used in this study. Vibration was the main parameter used for monitoring the machine. The vibration measurements were collected using Microlog and Presim[2] software. The measurements were all in mm/s, RMS. Vibration measurements of ten identical replaced spherical roller bearings of type 23228ck/SKF which are usually used at the driven side of the leading roller of drying cylinders in PM1 formed part of the data. There were no enough replacements from other types to be included. According to the personnel experience, the most troublesome area in the machine was the drying cylinder group. This is why these bearings were selected. The vibration measurements made at these ten bearing were few and done in three directions vertical, horizontal and axial. The measurements in the axial direction are analysed only because they represented bearing condition much better than the measurements in the other directions due to high stiffness and more informative spectra.

The vibration measurements, which cover the period under study (940901-941231), made at these roller bearings are collected from the machine database. The measurements are done only once/day at 940901, 940926, 941013, 941027, 941124, 941208, 941222. Records of machine operating conditions, which were usually registered 2-3 times/day and were reported manually in formal tables, are also gathered for the same period. The data which were formally considered in these reports were: Machine operating speed and load in specific parts of PM1 such as press and drying cylinder groups, number of stoppages and their times, reasons behind stoppages and the machine part where the failure happened, (if they were known). Paper quality and contents were also included. There is small risk for uncertainty in identifying the reasons, i.e. problem area, behind the short stoppages. This uncertainty is due to the deficiencies in the techniques used for detecting and localising any cut in the paper. They were using special lighting system connected to particular sensors which were installed along the paper machine to detect and localise if there is any cut in the paper. Sometimes, it is possible that the operator misses when the light was first activated and consequently the opportunity to identify where the cut is actually happened may be missed.

In order to distinguish the changes in vibration spectra, only the bearings which acquired two or more vibration measurements during the period 940901-941031 are considered significant for the study. The 3rd and 4th drying cylinder groups in the paper machine PM1 were considered for more analysis because they were identified by the company as parts of problem areas. The vibration measurements were picked up at the bearing houses of the driven side, (DS), of the lead rollers, (LR), 041, 056, 059, 064, 065, 072, 075, 080 and, 085 and 095, which lie in the third and fourth drying cylinder groups, respectively. Notice that not all the ten bearings at the driven sides of these LRs could be considered in the analysis

because there were no enough vibration measurements. At the bearings where more than one measurement were made during the period under analysis, data about the following are gathered from these measurements, see Tables 1, 2 and 3:

1. Machine speeds recorded by both the vibration technician and operator.
2. Amplitudes of the first multiple (1*X), second multiple, (2*X) and third multiple, (3*X) of the machine speed (in revolution per second), where X and i*. denote the machine rotational frequency and the ith multiple of the frequency, respectively.
3. Amplitudes of the frequencies at the range 15*X - 36*X. Frequencies at this range are, in general, correlated to the changes in the bearing condition [4].
4. The vibration levels which are usually indicated in the commercial vibration-based monitoring programs by one or more of the following:
   - Overall RMS vibration level, to represent the vibration energy in the whole vibration signal.
   - Synchronic RMS vibration level, i.e. the vibration energy in the harmonics to the machine speed frequency.
   - Sub-synchronic RMS vibration level, i.e. the vibration energy in the frequencies less than the machine speed frequency.
   - Non-synchronic RMS vibration level, i.e. the vibration energy in the frequencies which are not harmonics to the machine speed frequency.
5. The load at the third and fourth drying cylinder groups.

Analysis: Data from two types of the above mentioned reports, called report 1 and 2, covered the period 940901 - 941031, are analysed. The analysis is limited to this period due to the lack of more data. The variation in the machine rotational speed at the 3rd and 4th drying cylinder groups during the period under study is explained by the data plotted in Fig. 1. The variation in the machine load at these two cylinder groups, during the same period, is explained in Fig. 2. In reports 1 and 2, the stoppage time is divided into four categories based on the reasons behind stoppages, which are; unknown reasons, (O), miscellaneous, (T), shift in the tambour, (S) and slime, (K). The total stoppage time was about 4593 minutes. The major part of it, about 3980 minutes which is 87% of the total stoppage time, was actually because of unknown reasons, see Fig. 3. The next longest stoppage time, about 475 minutes, i.e. 10% of the total stoppage time, accumulated due to miscellaneous. The latter was not defined in the reports and eventually can be added to the unknown reasons. The machine part behind stoppages are classified into eight areas which are: the 2nd press

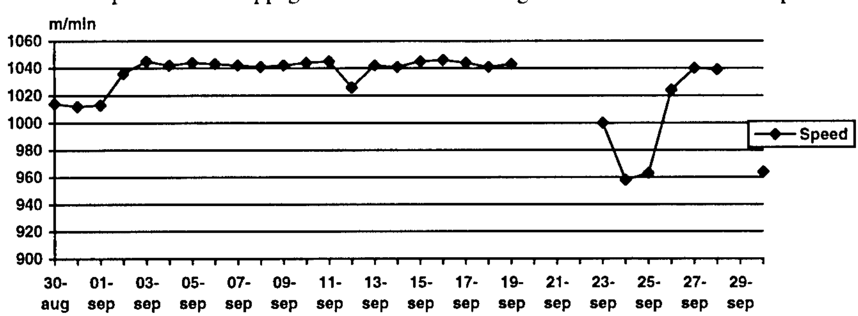

Fig. 1. The variation of the machine speed at the third and fourth drying cylinder groups, PM1. The discontinuity in the curve is due to lack of data at some days.

cylinder group, 3rd press cylinder group, 1st drying cylinder group, 2nd drying cylinder group, 3rd drying cylinder group, 4th drying cylinder group, calender and pope, see Fig. 4. The plot shown in Fig. 4 displays that the stoppage times accumulated due to failures in the 3rd press cylinder group, 1st and 2nd drying cylinder groups and Calender are; 1370, 1120, 786 and

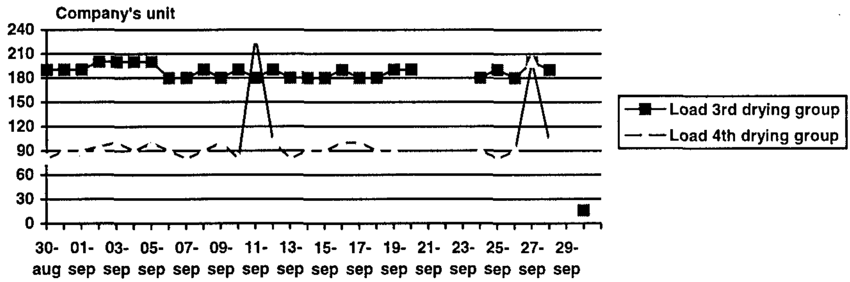

Fig. 2. Variations of the machine load at the 3rd and 4th drying cylinder groups, PM1. The discontinuity in the curve is due to lack of data at some days.

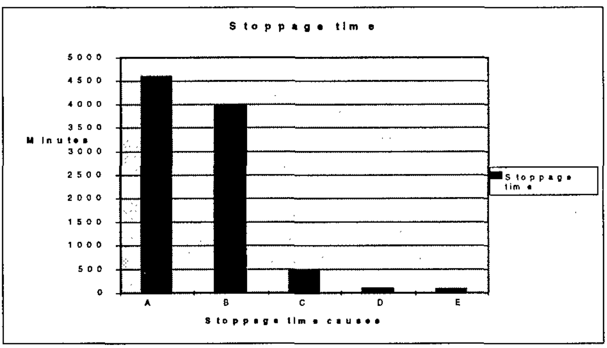

Fig. 3. Total stoppage time, (A), stoppage time due to unknown reasons, (B), stoppage time due to miscellaneous, (C), stoppage time due to shift in the tambour, (D), stoppage time due to slime, (E).

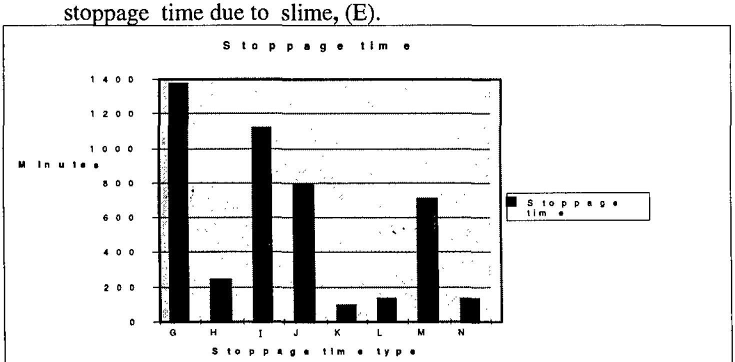

Fig. 4. Stoppage time due to; failures in the 3rd cylinder group, (G), failures in the 3rd press cylinder group, (H), failures in the 1st drying cylinder group, (I), failures in the 2nd drying cylinder group, (J), failures in the 3rd drying cylinder group, (K), failures in the 4th drying cylinder group, (L), failures in calender, (M), failures in pope, (N).

709 minutes, respectively. The number of stoppages experienced by PM1 during this period was about 490 stoppages. It is obvious that there exist distinguishable differences between the machine speeds measured by the operator and that recorded by the vibration technician, see Tables 1, 2 and 3. The minimum differences, about 0 and + 0.02 revolution per second, (rps), were experienced in 941013 and 941222, respectively, and the maximum differences, about 0.85 and 0.75 rps, were in 940901 and 941208, respectively.

The time of the vibration measurement.	941013, 07:13	941027, 06:10
Machine speed measured by vibration technician	547 rpm = 9.12 rps	510 rpm = 8.5 rps
Amplitudes of 1*X, 2*X, 3*X, 4*X, 6*X & 7*X and 8*X	0.31, 1.45, ----, ----, ---- & ---- and 0.17 mm/s	0.24, 1.14, ----, 0.55, ---- & ---- and ----, mm/s
Amplitudes of the frequencies within the range	(194-316) Hz, were 0.17-0.32 mm/s	and (216-312) Hz, were 0.13-0.25 mm/s
Overall RMS	2.04 mm/s	1.71 mm/s
Synchronic	1.88 mm/s	1.61 mm/s
Sub-Synchronic	0.10 mm/s	0.10 mm/s
Non-synchronic	0.79 mm/s	0.57 mm/s
The load at the drying cylinder group	200 company's unit	200 company's unit
Rotational speed according to the operator where the diameter of the cylinder = 605 mm	1040 m/min. = 9.12 rps 941013, 06:00	1006 m/min. = 8.82 rps 941027, 06:00
Differences in rps: (speed measured by vibration technician - speed measured by operator)	0 rps	- 0.32 rps

Table 1. The bearing at the DS of the LR 56 in the axial direction, LR 056 DS A.

The time of the vibration measurement.	941013, 07:52	941222, 09:37
Machine speed according to the vibration technician	547 rpm = 9.12 rps	539 rpm = 8.99 rps
Amplitudes of 2*FTF, FTF: Fundamental train frequency 2*X+2*FTF 1*BPFI, 2*BPFI, BPFI: Ball pass frequency inner. 3*BPFO, BPFO: Ball pass frequency outer. 2*BPFI+2*FTF 3*BPFO+2*FTF 8*BSF, BSF: Ball spin frequency.	0.25, 0.18, 0.36, 0.15, 0.14, ----, ---- , ----- mm/s	---, ---, ---, 1.83, 11.61, 1.13, 1.38, 2.15 mm/s
Amplitudes of 1*X 2*X 16.5*X 20.5*X	0.25, 1.5 , ----, ---- mm/s	1.1, ----, 1.4, 0.97 mm/s
Amplitudes of the frequencies in the range	(100-466 Hz), were about 0.14-0.30 mm/s	(100-440 Hz) were about 0.8- 11.6 mm/s
Overall RMS	1.98 mm/s	13.32 mm/s
Synchronic	1.86 mm/s	8.85 mm/s
Sub-Synchronic	0.12 mm/s	0 mm/s
Non-synchronic	0.66 mm/s	9.95 mm/s
The load at the drying cylinder group	200 company's unit	200 company's unit
Rotational speed according to the operator where the diameter of the cylinder = 605 mm	1040 m/min. = 9.12 rps 941013, 06:00	1023 m/min. = 8.97 rps 941222, 06:00
Differences in the speed: (speed measured by vibration technician - speed measured by operator)	0 rps	+ 0.02 rps

Table 2. The bearing at the DS of the LR 75 in the axial direction, LR 075 DS A.

The differences in the speed measurements were positive, i.e. the speed recorded by the vibration technician was higher than that registered by the operator. But, the measurement made in 941027 at LR 056 was -0.32 rps. All the frequencies specified in Table 1 acquired higher amplitudes at the higher machine speed independent of the machine load. This is also true in Table 3 when it concerns bearing defect frequencies, e.g. Fundamental Train Frequency, (FTF). The literature was found mainly to confirm this analysis see for example [1]. This is because the vibration levels due to, e.g. imbalance and misalignment are usually proportional to the machine speed. From Table 2, it obvious that high frequencies such as 16.5*X and 20.5*X acquired much higher amplitudes at 941222. The increment in the overall RMS vibration level is obviously due to the appreciable increment in the amplitudes of the synchronic and non-synchronic frequencies. All together may interpreted as indications of bearing defects which led finally to replace the bearing at 941226. The machine load was the same at the two opportunities. The differences in the recorded speed registered by the operator and vibration technicians are negligible.

The time of the vibration measurement.	940901, 07:01	941208, 15:28
Machine speed according to the vibration technician	584 rpm = 9.73 rps	548 rpm = 9.13 rps
Amplitudes of	2* FTF = 1.96 mm/s	2*FTF = 0.55 mm/s
Amplitudes of the frequencies	100-300 Hz are about 0.16-0.6 mm/s	100-560 Hz are about 0.17-0.6 mm/s
Overall RMS	1.92 mm/s	2.53 mm/s
Synchronic	1.62 mm/s	2.45 mm/s
Sub-Synchronic	0 mm/s	0 mm/s
Non-synchronic	1.03 mm/s	0.64 mm/s
The load at the drying cylinder groups	190 company's unit	180 company's unit
Rotational speed according to the operator where the diameter of the cylinder = 605 mm	1013 m/min. = 8.88 rps 940901, 06:00	957 m/min. = 8.38 rps 941208, 06:00
Differences in the speed: (speed measured by vibration technician - speed measured by operator)	+ 0.85 rps	+ 0.75 rps

Table 3. The bearing at the DS of the LR 67 in the axial direction, LR 067 DS A.

Results and Discussions: The plot of the stoppage time accumulated due to failures in the machine parts specified, see Fig. 4, reveals that the problem areas ranked according to their economic importance are the 2nd press cylinder group, 1st and 2nd drying cylinder groups and Calender. The problem areas distinguished by this study contradict those which were identified based on the personnel experience. Machine rotational speed and loading were not constant during operation, and they varied partly stochastically and partly according to production plans. The result of data analysis presented in Tables 1, 2 and 3 reveal appreciable changes in the vibration amplitudes of the frequencies specified when the machine speed and load were changed at the different operating conditions. The machine speed was always recorded by the vibration technician at the times when vibration measurements were done in addition to the record kept by the operator which includes one or two measurements of the speed daily. In most cases, the machine speeds recorded by the vibration technician and operator were made at different times of the day. This may cause some uncertainty in the differences of the speeds recorded by these two persons.

Almost all the frequencies stated in Table 1.reveal higher amplitudes at lower machine speeds. The reason is probably due to the initiation of bearing defects during the interval followed the first measurement, i.e. during the period 941013-941222. The rapid development of these defects resulted finally in the replacement of the bearing at 941226. In

Table 3, the bearing defect frequencies, represented by FTF and the non-synchronic frequencies, acquired higher amplitudes while all the other frequencies acquired lower amplitudes. This is probably due to the higher load, i.e. higher load may result in high amplitudes in the bearing defect frequencies. This is true because changes in the machine speed may cause bearing defect frequencies only to shift.

Dynamic Alarm: The alarm levels are usually set by a person not well trained for such tasks. It is rare that this person has the required knowledge of machine design, failure causes, defect development mechanisms, failure modes, identifying the significant frequencies and their relation to defects, etc. The setting of envelope alarm is, in general, done by "experts", but the possible changes in the machine speed, which cause frequency shift, are usually not handled reliably. When monitoring a vibration spectrum, the useful data to be observed are: The significant frequencies, amplitudes of the significant frequencies, new and disappeared frequencies and the noise level. The significant frequencies are those which can be utilised to assess which machine elements are deteriorating and the damage severity, and to track defect development. In the commercial VBM programs, which are usually used in paper mills, there are three types of alarms; Overall alarm to monitor the overall vibration energy, envelope alarming to monitor all the spectral patterns, and selective frequency band alarming. Overall vibration energy is the main factor for establishing tables for alarm systems [5]. The statistical alarm limits are usually based on some unrealistic assumptions such as normality of the vibration measurement values even during the defect development phase [6,7]. At alarm, extra vibration measurements at more frequent intervals are usually made before taking a decision on when to renew the bearing.

A dynamic envelope alarm consists of several warning levels and is prepared in advance, i.e. bearing significant defect frequencies are identified in the envelope alarming as multiples of the machine speed, and normalised to 1 Hz, (1 rps). Thus, it would be applicable for identical bearings and those of approximately identical vibration signatures and independent of the machine speed because frequencies are identified relative to the actual rps. Particular warning messages arise indicating deterioration severity and which frequency(ies) is (are) involved. Three levels would, however, be necessary to indicate defect initiation, development and the replacement level [8], but this is rarely done. Significant frequencies and amplitudes can be determined from the machine vibration history. Different operating conditions may cause variations in the vibration signature, i.e. new frequencies and different amplitudes, which were not considered in the original envelope alarming. The user should have the opportunity to change the envelope alarming to fit the operating conditions.

Identification of defect causes is not easy for the technician especially, when thousands of measuring points are required to be assessed say monthly. By means of a software program, which is prepared specially for identification of defect causes, it is possible to identify characteristic defect vibration frequencies and evaluate the state of the interesting bearings easily and effectively. The available tools are not effective enough due to their inability of considering changes in the machine speed, bearing defect frequencies and operational conditions. The assessment of the bearing state should become easier when the dynamic envelop alarm is established and has run for a while to accommodate data. Alarm setting for each measuring point should be handled by software.

Example: The data used in this example are not all real but they are reasonable and based on the author's practical experience within paper mill industry. Assume that we have n nominally identical rolling element bearings installed at the driven sides of n drying cylinders, in a paper mill machine. In such a case the bearings can be considered to be exposed to approximately the same operating conditions, such as load, speed and temperature. Let the vibration frequencies which can be used to detect and follow damage developments in these bearings at an early stage be; 1*BPFO, 2*BPFO, 1*BPFI, 2*BPFI, 1*SBF, 2*SBF, 1*FTF, 2*FTF, (1*FTF+1*BPFO), (1*FTF+BPFI) and (1*SBF+1*BPFO) [2]. Also, let the three alarm levels, i.e. defect initiation, development and replacement, of each of these frequencies be; (0.3, 0.5, 0.95), (0.2, 0.35, 0.85), (0.25, 0.4, 0.9), (0.2, 0.4, 0.8), (0.3, 0.4, 0.9), (0.25, 0.35, 0.8), (0.2, 0.4, 0.8), (0.15, 0.3, 0.6), (0.15, 0.3, 0.6), (0.2, 0.4, 0.7) and (0.2, 0.3, 0.6), respectively, measured in mm/s. These levels can be estimated from the VBM database for the machine when enough identical bearing replacements have been recorded [2,7,8]. Make the alarm level at each frequency cover a range equal to 1.5% at either side of the designated frequency to compensate for the variations in the bearing defect frequencies. It is possible then to set the three-level envelope alarm for the above frequencies, manually or through the software. For easiness, let the location of each of the chosen vibration frequencies in the envelope alarm shift to the right or left precisely the same amount of increment or reduction in the planned running speed, respectively. Also, let the alarm levels increase or decrease by double the amount of increment or reduction in the planned load, respectively. Now, assume that at time $t_2 > t_1$, the vibration and operating conditions are measured once more simultaneously, and it is found that the vibration spectrum is not appreciably changed, but the running speed and load are increased by 10% each. This means that all bearing defect frequencies are shifted by about 10% to the right of their original positions and their amplitudes are increased by at least 20%. In this case, using a three-level dynamic envelope alarm, which should be adjusted manually (or automatically), no warnings would be expected even if operating conditions are changed appreciably, see Fig. 5.

However, this is not possible if the envelope alarm is not adjusted, which is the case in general when using commercial VBM programs including one or, sometimes, two-level envelope alarms. Thus, the replacement of the bearing is indicated even though it is still functioning. For example, frequency b=112.1 Hz, which has 0.5 mm/s amplitude, will shift to the right by about 11 Hz and its amplitude may increase to 0.6. This means that frequency b will shift to the range which is very close to that occupied previously by the frequency (f+b)=117 ± 2 Hz. In other words, frequency b would exceed the third envelope alarm level and lead to unnecessary bearing replacement, when the real amplitude of frequency b remained at only 52% of the replacement level 0.95 mm/s, see Fig. 5. In general, using a three-level envelope alarm, whether dynamic or not, for bearing defect frequencies increases the bearing's useful life, because the bearing is usually replaced as soon as its vibration level exceeds the normal, i.e. when it is still below the second alarm level [8]. A dynamic three-level envelope alarm would increase the bearing useful life appreciably and reduce the number of planned and unplanned replacements because the ambiguities, which arise due to changes in speed and load, and cause inaccuracy in the assessment of the bearing condition, will be eliminated. In many cases, setting and adjusting envelope alarms manually is very difficult and expensive especially when it concerns thousands of measurement points. Now, if these three envelope alarms are normalised to one RPS and produced in a software program, which is automatically

adjustable depending on operating conditions, then envelope alarm setting and adjusting for all n bearings will be easier and cheaper.

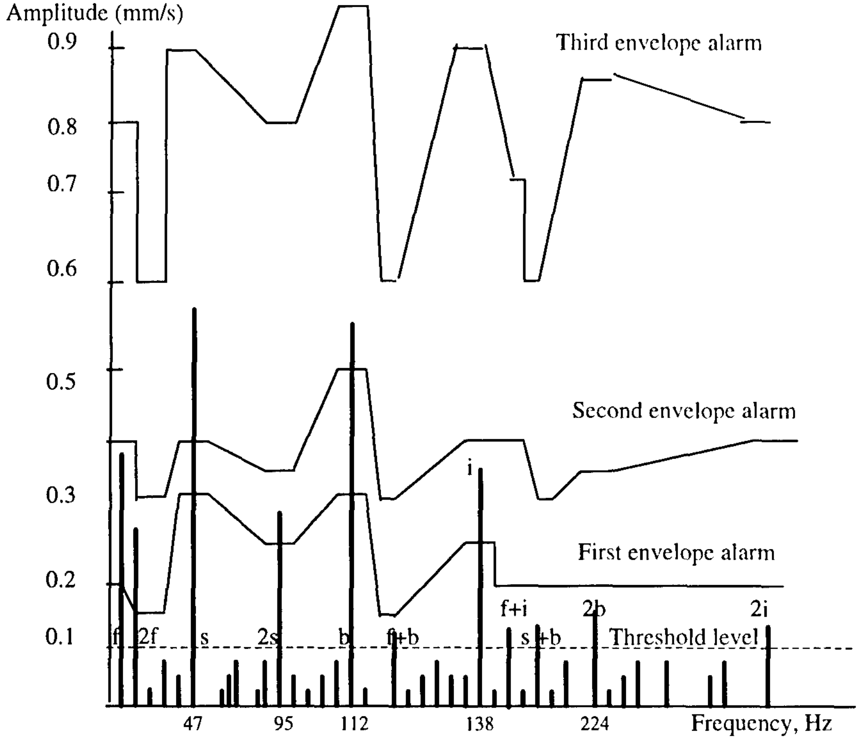

Fig. 5. A typical vibration spectrum reveals only the defect vibration frequencies of the bearing 23052 cck/SKF and the three assumed envelope alarm levels, where b, 2b, i, 2i, s, 2s, f, 2f, (f+b), (f+i) and (s+b) are 1*BPF0, 2*BPFO, 1*BPFI, 2*BPFI, 1*SBF, 2*SBF, 1*FTF, 2*FTF, (1*FTF+1*BPFO), (1*FTF+BPFI) and (1*SBF+1*BPFO), respectively. The speed is assumed to be 10 rps. For the bearing 23052 cck/SKF, FTF=0.45 Hz, SBF=4.73 Hz, BPFO=11.21 Hz and BPFI=13.79 Hz, all normalised to 1 rps. All the frequencies below the threshold level are considered insignificant.

Conclusions: It is beneficial to keep real-time measurements of the operating conditions particularly the machine speed and load to be used in conjunction with the vibration measurements, to eliminate ambiguities in deciding whether the increase in the vibration level is due to more deterioration or to the increment in the operating conditions. The second press cylinder group, first and second drying cylinder groups and Calender are identified in this study as the essential problem areas in the machine under consideration. The total stoppage time due to unknown reasons was very large and causes appreciable economic losses, about 2,3 millions SEK during fifty eight days (this is calculated in the basis that each hour causes losses equal to about 30 000 SEK). Thus, it would be beneficial

to invest in the work aims to analysing and eliminating the basic reasons behind these economic losses.

Due to the lack of enough and reliable data, the analysis were limited to few rolling element bearings which made the results in the form of indications instead of statistical evidence. Thus, better data coverage and quality from the surroundings and more frequent vibration measurements help to achieve many goals such as detecting defect initiation and following its development, effective diagnosis and prognosis, effective control of the condition of machinery and production losses. The dynamic envelope alarm is shown theoretically to offer later renewal with fewer failures, and therefore lower cost and higher productivity. Using the dynamic envelope alarm, it is possible to identify defect vibration frequencies and to evaluate the state of the bearings easily and effectively.

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Energy Dispersive X-Ray Fluorescence Evaluation of Debris from F-18 Engine Oil Filters

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Abstract: Traditionally, the primary analytical instrument that monitors the "health" of mechanical oil systems in the U.S. Department of Defense (DoD) and Canadian Department of National Defence (CDND) is rotrode atomic emission spectroscopy (AES). The engine oil filter installed in the F-18 engine captures particles from the engine oil stream as small as 0.3 microns. This phenomenon renders AES surveillance of the F-18 engine oil system ineffective in detecting abnormal wear and impending engine failure. The debris that is extracted from the F-18 engine oil filter and captured on external filter media contains all the information necessary to detect abnormal wear and engine failure in the oil wetted sections of the F-18 engine. However, the debris is not in a suitable form to be analyzed by AES and requires considerable effort, time and hazardous chemicals to transform the debris into a form suitable for analysis by AES.[1] A method has been developed at the JOAP-TSC that utilizes Energy Dispersive X-Ray Fluorescence (EDXRF) to analyze the debris extracted from the engine oil filter and captured on filter media with little effort. Warning levels for elements have been statistically derived. The EDXRF Filter Debris Analysis (FDA) method provided 100 or more operating hours of advanced warning of engine failure. In addition, the EDXRF-FDA method can indicate the areas of wear in the engine. The Canadian Forces (CF) at Trenton in conjunction with GasTops LTD have developed and tested a prototype Deployable Filter Debris Analysis (DFDA) machine that automatically cleans F-18 engine oil filters. The instrument also segregates particles according to size and ferromagnetic properties. A comparison is made between the evaluations of the particles on the DFDA filter and EDXRF analysis of the same particulate samples.

Keywords: Energy Dispersive X-Ray Fluorescence, rotrode Atomic Emission Spectroscopy, Ferrography, wear condition.

Introduction: The JOAP-TSC has developed a method to analyze the debris from lubricant filters utilizing Energy Dispersive X-Ray Fluorescence (EDXRF). EDXRF is a mature technology however, the methodology and interpretation of the EDXRF signal developed at the JOAP-TSC is a novel, cutting edge approach to applying EDXRF technology. The EDXRF- Filter Debris Analysis (FDA) technique is able to characterize debris from the F404 engine oil system, an extraordinarily fine filtered lubricant system, and yields a condition monitoring technology that can predict failure 100 hours in advance.

Background: Rotrode atomic emission spectroscopy (AES) has been used as the primary analytical tool for monitoring the condition of weapon systems in the U.S. Department of Defense (DOD) and the Canadian Department of National Defence (CDND) for a number of years. The advantages of using AES include the following:
--- high numbers of samples can be analyzed per hour --- approximately 30 samples per hour
--- simultaneous determination of 15 elements in lubricants
--- no sample preparation required
However, AES has limitations:
--- can not detect particles larger than 8-10 microns [2],
--- matrix interference from the lubricant and
--- ineffective as a condition monitoring tool for lubricant systems equipped with 3 micron absolute filtration

Particle counting offers insights into monitoring the condition of weapon systems. Particle counting yields the following:
--- high numbers of samples can be analyzed per hour --- approximately 25,
--- distribution of particles by sizes,
--- particle populations in specific particle size ranges and
--- particulate loading of the system
Particulate analysis has limitations:
--- fine filtration is a problem,
--- no information about the elemental composition of the particles,
--- no information on the source of the wear particulates and
--- yields gross indication on the wear condition of the machine.
For particulate analysis to be successful, it must be used with a technology that can identify the elemental composition of the particles.

Ferrography is a methodology in which microscopic examination of particles is performed to classify the particles by particle morphology. It offers the analyst a method to do the following:

--- Classify the shapes of particles as originating from surfaces experiencing cutting, sliding, bearing, etc. wear and

--- can be related to wear modes experienced by the machinery.

Ferrography has disadvantages:

--- time per sample is high -- up to 1 hour per sample

--- requires intensive training,

--- labor intensive

--- fine filtration of lubricant systems is a problem for ferrography of a lubricant sample and

--- only empirical identification of particles can be achieved by observing the color of particles, heat treatment of particles to observe color changes associated with temperature and by employing other, chemical analytical methods to identify particle composition.

Fine filters are employed in lubricant systems to eliminate the recirculation of particles larger than 3 microns through the lubricant system. The particles are deemed harmful and the elimination of the particles by the fine filter, 3 microns and above, would greatly reduce the secondary wear these particles could induce. The inability of AES to monitor fine filtered lubricant systems and the subsequent removal of weapon systems equipped with fine filtration mean that other techniques, e.g., magnetic chip detectors, physical property analysis, etc., are employed in an attempt to monitor the wear condition of these weapon systems. Magnetic chip detectors are inefficient and are designed to only capture ferromagnetic particles. In the F404 engine, there are numerous alloys that are not ferromagnetic, but are critical to assessing the wear condition of the engine and in detecting the onset failure modes in the F404 engine. The success of a magnetic chip detector depends upon the size of the particle, morphology of the particle, strength of the magnetic field and the location of the chip detector.[3] Another approach to reducing failures is to change out components, modules, etc. based solely upon the amount of time the component or module is in operation. This can be an effective technique to reduce the number of failures. Even though all of these techniques are used to directly or indirectly monitor the condition of fine filtered systems - magnetic chip detectors and physical property analysis in conjunction with the removal of components or modules based upon the time they are in operation - a fine filtered lubricant system like the F404 engine still experiences failures.[4]

Table 1 depicts a few examples of weapon systems or components that had been monitored by AES, but were removed from monitoring due to fine filtration or because AES is ineffective in predicting the abnormal wear and onset of the failure modes of the weapon system. The F404 engine used in the F-18 aircraft is the focus of this study. The F404 is equipped with three separate lubricant systems - Airframe Mounted Accessory Drive (AMAD), engine lubricant system and Variable Engine Nozzle (VEN). Each system is lubricated with MIL-L-23699 synthetic oil and has an oil filter. The subject of the EDXRF study is the debris extracted from the engine oil filter.

SERVICE	EQUIPMENT MODEL	AIRCRAFT MODEL	ENGINE/ GEARBOX	REASON FOR REMOVAL FROM DoD OIL ANALYSIS PROGRAM
US NAVY	F404-GE-400	F-18 (JET)	ENGINE	AES NOT EFFECTIVE IN DETECTING FAILURES
US NAVY	T700-GE-401/401C	SH-60 (HELICOPTER) T700-GE-401/401C	ENGINE	3 MICRON FILTRATION
US ARMY		UH-60 (HELICOPTER)	ENGINE AND GEARBOXES	3 MICRON FILTRATION
US ARMY	T400-CP-400	AH-1 (HELICOPTER)	ENGINE	3 MICRON FILTRATION
US AIR FORCE	T56-A-14/16/425/427	C-130 (TURBOPROP)	ENGINE	AES NOT EFFECTIVE IN DETECTING FAILURES
US AIR FORCE	F404-GE-F1D2	F-117 (JET)	ENGINE	3 MICRON FILTRATION

Table 1. Components of Weapon Systems Removed from AES Surveillance.

Theory: An oil sample taken from a lubricant system is a "grab" sample. The analysis of an oil sample by AES represents the condition of the lubricant system at the time the oil sample is taken. The optimum choice for spacing of the oil samples is dependent upon the type of failures experienced in the past by the system being sampled. The assumption is that the wear condition of the machine in the intervals between samples is predicted by the oil samples taken at specific intervals. Ideally, oil sampling intervals are adjusted to reflect the findings of the failure analyses for the weapon system and to detect the onset of abnormal wear and the onset of failure modes. The oil sampling intervals must be close. This is why a high frequency of sampling must be done to monitor a machine with AES.

The debris extracted from an oil filter represents an accumulation of information about the lubricant system for a period of time; e.g., F404 engine oil filters are removed every 200 hours of operation. The debris accumulated by the filter represents 200 hours of wear. No assumptions need to be made about the wear condition of the engine in the 200 hour interval between filter removals. The wear history has been accumulated by the engine oil filter. The filter in the lubricant system of the F404 engine is a 10 micron nominal, 15 micron absolute filter. This does not qualify it as a fine filter. However, the MIL-L-23699 synthetic oil becomes slightly carbonized by the hot sections of the engine. The slightly carbonized oil coats the oil filter and transforms it into an extremely fine filtering device. Particles as small as 0.3 micron are captured by the filter.

Fine filtered systems present no problems for analysis by the EDXRF-FDA method. EDXRF is the type of x-ray measurement made in this study. EDXRF spectroscopy is a non-destructive determination of elemental composition and provides simultaneous analysis for elements in a sample. A sample is exposed to x-ray photons emitted from an x-ray tube. The sample absorbs some of the x-rays and then emits x-rays of its own in a process called fluorescence. The resulting fluorescent x-rays are characteristic of the elements in the sample. The EDXRF instrument used in this study incorporates a lithium drifted silicon detector to detect the fluorescent x-ray photons emitted from the elements in the sample. The detector absorbs the x-rays individually and produces a pulse with a voltage proportional to the x-ray energy of the photon. Electronic separation of the pulses according to their height yields a photon energy spectrum,[5] a process known as energy dispersion. This spectrum contains the information identifying which elements are present in the sample and the quantity of each element in the sample.

The basic atomic mechanism for producing x-ray fluorescence may be understood by considering the interaction of the incoming x-ray with the atomic electrons. Electrons are oriented around elements in energy shells. The electrons of interest in EDXRF analysis are in the K, L and M inner energy shells.[6] The K electrons are in the energy shell closest to the nucleus and are the most tightly bound electrons in the atom. An x-ray photon emitted from the source, an x-ray tube, can impinge upon an element's electron and cause the ejection of the electron, leaving behind an orbital vacancy. An electron from another energy shell can move into this vacancy with the emission of an x-ray photon, a process called fluorescence. The emitted x-ray photon carries an energy equal to the difference in the binding energies of the two energy shells, e.g. the more loosely bound outer shell binding energy is subtracted from the binding energy of the more tightly bound inner shell.[6] The value of the emitted x-ray photon's energy is characteristic of the element. This is a simplified explanation of the process and omits other possible interactions, but is quite sufficient for a basic understanding of the relevant processes.

The EDXRF analysis of a large piece, an inch or more in diameter, of metal alloy with a specific composition of elements is straightforward. Thickness is the important dimension for macroscopic samples, all dimensions are important for small particles less than approximately 100 microns. The percentages reported by an EDXRF spectrometer

analysis can be related to the concentration of each element in the alloy. However, the debris from oil filters is composed of metal particles from many different alloys. The percentage of a given element in this mixture of several alloys does not have the same meaning as the percentage of the element in a single alloy and is not directly related to the elemental concentrations in any of the individual particles. The elemental analysis of wear particulates by EDXRF, for the purposes of condition monitoring, can be carried out quite effectively by a statistical analysis of the percentages alone without addressing the theoretically complicated issue of concentration for these particulates.

The particulate sample is also different from the bulk sample. A sufficiently thin sample will produce fewer total fluorescent x-rays, although the average number of fluorescent x-rays per atom will be greater than for a bulk sample. The x-ray spectral data was analyzed by an approach called thin film analysis. Thin film analysis applies where all of the atoms that compose the film transmit essentially all the fluorescent x-rays, which occurs for films and debris samples having a maximum thickness of about 1 micron. [7] The real samples of wear particulates prepared in this application are a mixture of infinitely thin films and intermediate thickness films (that fall between thick films and infinitely thin films). Such thickness effects, when discussed in terms of particulate samples, are often referred to as particle size effects. Fortunately, the effect of particle size is to increase the measurement sensitivity for smaller particles and is accounted for in the statistical analysis of the data.

Intermediate thickness films, large particles, and bulk samples of alloys can exhibit matrix effects, where the fluorescent intensity radiated, per atom of a given element, depends upon the alloy composition. This complication can be handled with a Fundamental Parameters (FP) calculation. The FP calculation produces the matrix correction factors (alphas) and the estimate of sample thickness. The FP calculation estimates the thickness by comparing measured x-ray intensities to theoretical x-ray intensities expected from a sample of a given thickness. The FP calculation goes through iterations until the program finds the thickness which matches the theoretical x-ray intensities with the measured x-ray intensities. Once the thickness is found, the matrix correction factors (alphas) are calculated for the unknown sample.[7] Once the FP analysis is complete, the corrected data may be analyzed and compared with the engine history.

Application: The F404 engine is a modular engine. The debris extracted from the F404 oil filter is deposited on a 1 micron polycarbonate filter. The procedure is too detailed to present here. [8] The debris is analyzed on a Spectrace 6000 EDXRF spectrometer. In this study, 189 filters were analyzed. For each filter, EDXRF index values were calculated for each of the 18 elements analyzed by the spectrometer. Two index values were calculated for use in comparing filter content with engine condition.

To calculate the Element Percent Index (EPI), the fluorescent x-ray counts (intensity) recorded by the spectrometer for each element are divided by the total counts measured during the time of the analysis of the sample. The readout for each element is expressed

as a percentage. This percentage is normalized to 100%. In this study, the percent of each of the elements reported is treated only as a percent of the total counts for all elements accumulated for that filter during the period of analysis. The levels of significance were set by a statistical analysis of the entire set of normalized percentage data, for that element, from all available filters. Each element has 189 normalized percentage results, one per filter. The mean and standard deviation for each element's normalized percentage is calculated. A percentage exceeding the value of the mean plus three standard deviations is considered an outlier. Percentages that are outliers are labeled with a 5 level of significance. The outlier values represent the highest percentage values of an element in the oil filter debris. The mean and standard deviation are recalculated omitting the outliers. Levels of significance are assigned to each recalculated percentage. If the percent of the element is less than or equal to the (recalculated) mean plus one (recalculated) standard deviation, the percent for the element is assigned a level of significance of 1. If the percent for the element is greater than the mean plus 1 standard deviation and less than or equal to the mean plus 2 standard deviations, the percent for the element is assigned a level of significance of 2. If the percent for the element is greater than the mean plus 2 standard deviations and less than or equal to 3 standard deviations, the percent for the element is assigned a level of significance of 3. If the percent for the element is greater than the mean plus 3 standard deviations, the percent for the element is assigned a level of significance of 4. The level of significance values just described are defined as the EPI.

In this way, the statistical levels of significance for each sample's elements are derived from the EDXRF spectrometer's normalized reported percentages. The more an element's normalized percentage deviates positively from the mean, the higher the level of significance assigned to the element's percentage, e.g. 1, 2, 3, 4 or 5. A level of significance for an element of 1 or less is considered "Normal" wear. A level of significance of 4 or 5 signifies an element's percentage had a very large positive deviation from the mean, suggesting advanced, detrimental wear.

The Element Thickness Index (ETI) is calculated in the same fashion as the EPI, but the normalized percentages are first all multiplied by the thickness value obtained from the FP calculation for that filter sample. The ETI was developed to take into account the total amount of material in the sample, while also characterizing the significance of the element's presence in a sample. Again, levels of significance are attached to each element's thickness index. The levels of significance of each element's thickness index are derived by the same process as the EPI levels of significance.

This empirical approach to developing a set of indexes allows for the identification of the elements present and the calculation of statistical levels of significance for each element. The mere presence of an element is not enough to indicate a problem, unless the EPI or ETI for that element is abnormally large.

A shorthand notation was developed for use in tabulating the index values. The EPI notation is composed of the element's chemical symbol and a numerical designation of 2,

3, 4 or 5 followed by a "P", e.g. Ti-5P for titanium with a significance level of 5. The ETI notation has the element's chemical symbol and a numerical designation of 2, 3, 4 or 5 followed by a "T", e.g. Ti-5T.

The EPI and ETI values for all 189 filters were computed. EDXRF guidelines were developed after a detailed consideration of comparisons between the EDXRF results and the metallurgy of the F404 engine. The EPI and ETI values which satisfy the guidelines are then used to identify the engine modules which are producing the wear particles. The F404 is a modular engine. Data tested by the above guidelines are then used to identify the source(s) of the analyzed wear particulates, Table 2, modules and and certain components within the module.

Elements	Level	Oil Pump	Oil Tank	AGB	F	HPC	HPT	LPT
Al	3,4,5	YES	YES	YES	YES	NO	NO	NO
Cu+Pb+Zn	2,3,4,5	YES	NO	NO	NO	NO	NO	NO
Fe	2,3,4,5	NO	NO	YES	YES	YES	YES	YES
Fe+V	2,3,4,5	NO	NO	YES	YES	YES	YES	YES
Ti	2,3,4,5	NO	NO	YES	YES	YES	NO	NO
Ti+V	2,3,4,5	NO	NO	YES	YES	YES	NO	NO
Ti+Sn	2,3,4,5	NO	NO	NO	YES	YES	NO	NO
Ti+Sn+V	2,3,4,5	NO	NO	NO	YES	YES	NO	NO
Ni	2,3,4,5	NO	NO	NO	YES	YES	NO	YES
Ni+Nb	2,3,4,5	NO	NO	YES	YES	YES	YES	YES
Co+Mo	2,3,4,5	NO	NO	NO	YES	YES	NO	NO
Cd*	2,3,4,5	NO	NO	NO	NO	YES	NO	YES
W*	2,3,4,5	NO	NO	NO	NO	YES	YES	YES
Ag*	2,3,4,5	NO	NO	YES	YES	YES	YES	YES
Si	3,4,5		DIRT	CON	TA	MIN	ATI	ON

*Elements considered if Fe, Ni and/or Ti are present.

Table 2. EDXRF-FDA Decision Matrix for Sources of Elements.

The EDXRF decision scheme can be easily adapted to the existing US Navy and Army oil analysis software, Oil Analysis Standard Interservice System (OASIS). This will provide an evaluation platform already familiar to field personnel.

Discussion of Results: To determine the critical metals in the F404 engine, a complete breakdown of the engine oil system components and alloy composition is required. From this information, a clear understanding is obtained for the probable sources of the elements. In parallel, the elements found by AES analysis of oil samples must also use the metallurgical composition of the components in an oil system to deduce the probable sources of the elements. The US Navy Aircraft Engine Maintenance System (AEMS) provides information about F404 engine maintenance. AEMS provides information about when maintenance was performed on an engine, the reason for the maintenance and the module or modules that were replaced. Using the AEMS information as a "standard" for correlating EDXRF-FDA results to AEMS data, a comparison was made between the EDXRF-FDA results and the AEMS information. The true measure of a condition monitoring technique and technology is its capability to give ample warning of an impending failure. Remarkably, this EDXRF-FDA technique predicted engine failure in every case that engine failure occurred. In this study, 27 oil filters representing 24 engines experienced failures of engine modules associated with the engine oil system. Twelve oil filters were removed prior to engine failure. Fifteen oil filters represent engine failures that coincided with the removal of the filter. In each case, this EDXRF-FDA technique:

(1) detected that advanced, detrimental wear was occurring,
(2) identified the elements in the wear debris, and
(3) correlated those elements with the module that failed.

The metallurgy of the F404 engine frequently eliminates some modules from consideration, while narrowing the scope to a few modules or even to a single module. This capability of the EDXRF-FDA method, to indicate the F404 module or modules that are the sources of the elements, is an additional feature above what is required of a condition monitoring method -- predicting impending failure.

An example will demonstrate the capability of the EDXRF-FDA method. Two oil filters, samples 1 and 2 respectively, were removed from F404 engine serial number 310656 at different times. Sample 1 engine oil filter was removed at 2418 Hours Since New (HSN). The elements of concern and their respective levels of significance are; Ti-4P, Ti-2T, V-4P, W-2P, Al-3P. This combination of metals, Ti, V and W, can originate from the HPC. Sample 2 engine oil filter was removed at 2515 HSN. The elements of concern and their respective levels of significance are; Ti-4P, V-4P, Sn-4P and Al-5P. Sample 2 indicates large and abnormal amounts of Ti, V and Sn being generated. The Ti, V and Sn indicate the wearing of Ti alloys. The abnormal amount of Al indicates a housing could be involved or severe corrosion exists. At 2660 HSN, AEMS indicated that engine serial number 310656 experienced an HPC failure. Sample 1 at 2418 HSN, indicated the HPC could be the source of the elements. The subsequent sample also confirmed the HPC was the source of the elements. This EDXRF-FDA

method indicated the HPC was the source of the elevated wear debris 142 operating hours before the HPC failed.

Deployable Filter Debris Analysis (DFDA): The Canadian Forces (CF) at Trenton in conjunction with GasTops LTD have developed and tested a prototype Deployable Filter Debris Analysis (DFDA) machine that automatically cleans F-18 engine oil filters. The instrument also segregates particles according to their size and ferromagnetic properties. Four filters for the particles extracted from each F404 lubricant filter were prepared by the DFDA as follows:

-- a filter with ferromagnetic particles 20 micron to <200 micron (20 micron F),
-- a filter with ferromagnetic particles 200 micron and greater (200 micron F),
-- a filter with nonferromagnetic particles 20 to <200 microns (20 micron NF),
-- and a filter with nonferromagnetic particles 200 microns and greater (200 micron NF).

The filters were analyzed by CF Trenton using ferrography terminology to identify the type of wear.[1] Ferrography is a method that separates particles from the oil by passing an oil stream down a glass substrate that is placed in a magnetic field. The size, morphology and color of the particles can be observed with the aid of a microscope. The information gathered from this analysis yields a concept of the type of wear occurring in the system. The pore size of the filters that captured the particles in the DFDA machine are not the same as the pore size, 1 micron, used to develop the EDXRF-FDA method. A new EDXRF-FDA database had to be developed to characterize the significance of the wear. The number of samples are limited, however some examples will demonstrate the correlation between the CF Trenton analysis of the DFDA filters and EDXRF-FDA method. EDXRF-FDA method will also yield considerably more detail about the composition of the particles on the DFDA filters and their relative significance. No maintenance data or pertinent information was available about the engines, therefore a correlation between actual maintenance performed on an engine and the EDXRF-FDA method and the CF Trenton filter analysis method could not be done.

An engine oil filter was taken from a U.S. F-18, F404 engine and labeled F20 USA. The DFDA machine produced a filter labeled F20 USA21 NF. The EDXRF-FDA elements and levels of significance and the CF Trenton filter evaluation are as follows:

SAMPLE NAME	ELEMENTS AND LEVEL OF SIGNIFICANCE	MODULES INDICATED	CF TRENTON DFDA FILTER ANALYSIS
F20 USA21NF	Fe-2P, Ag-3P, Al-5T, Ti-5T, Cr-2T, Fe-5T, Zn-3T, Cu-4T, Mo-5T, Ag-5T, Sn-2T	Ag Plating, Bearing Wear and Ti with Sn Alloy - F,HPC; High Al - Oil Tank, Oil Pump, AGB, F.	Heavy amounts of Al cutting and gear wear and what appears to be carbon particles.

The CF Trenton filter analysis of the nonferrous debris captured on the 20 micron filter states that they observed heavy amounts of Al cutting and gear wear. The elements and levels of significance that are important to the evaluation of the condition of the engine in this EDXRF-FDA method are: Fe-2P, Ag-3P, Al-5T, Ti-5T, Fe-5T, Ag-5T and Sn-2T. The EDXRF-FDA method agrees that there is a very significant amount of particles or loading of debris composed of Al on the filter as designated by Al-5T. The 5 level of significance is the highest level signifying an extraordinary value, an outlier, in the analysis of the data. The "T" means that this value is taken from the loading of the filter. The heavy amount of gear wear particles observed by CF Trenton signifies Fe and the EDXRF-FDA method agrees about the significance of the presence of Fe by the Fe-2P and Fe-5T ratings. The EDXRF-FDA method also detects significant levels of Ti alloy that was not observed by the CF Trenton analysis of the filter. Ti is one of the three primary metals that the EDXRF-FDA evaluation of the F404 engine oil filter debris is based upon. Another metal, Ag is seen by the EDXRF-FDA method, but is not observed in the CF Trenton evaluation. Also, a key indicator element that could not be observed by the CF Trenton analysis, Sn, is present. The modules indicated by the elements detected by the EDXRF-FDA method, Fe-2P, Ag-3P, Al-5T, Ti-5T, Fe-5T, Ag-5T and Sn-2T, indicate that the Fan and High Pressure Compressor can be the sources of this combination of elements. The presence of the Al indicates the Oil Tank, Oil Pump, Accessory Gearbox, Fan could be the source of the Al. The presence of Al must be treated as a unique case. A failure mode in the F404 engine is initiated by the introduction of moisture through an intake vent. The moisture reacts with the synthetic oil, MIL-L-23699, and causes the synthetic oil to dissociate or chemically convert to the reactants that produce the synthetic oil, organic acids and the organic polyol. The acids can easily corrode the Al alloys present in the Oil Tank, Oil Pump, Accessory Gearbox, and Fan sections of the engine. Corrosion induced by the intrusion of water into the F404 engine oil system has been attributed as one of the mechanisms to induce bearing failure in the accessory gearbox.[9] The possibility of Al being generated by corrosion resulted in the level of significance for Al being 3, 4, or 5 to be considered in an evaluation. However, damage to a housing must be considered at a level of significance for Al of 4 or 5. The EDXRF-FDA method offers areas of the engine as sources for the elements whereas the CF Trenton filter analysis method can not.

The second 20 micron filter prepared from the debris extracted from the F20 engine oil filter is labeled F20 USA 21F. The EDXRF-FDA elements and levels of significance and the CF Trenton filter evaluation are as follows:

SAMPLE NAME	ELEMENTS AND LEVEL OF SIGNIFICANCE	MODULES INDICATED	CF TRENTON DFDA FILTER ANALYSIS
F20 USA 21F	V-2P, Fe-3P, Mo-3P, V-5T, Cr-3T, Fe-4T, Ag-2T, Mo-5T	Ag Plating, Bearing Wear - AGB, F, HPC, HPT, LPT.	Heavy amounts of Fe laminar, sliding and gear wear and what appears to be carbon particles.

The CF Trenton filter analysis of the ferrous debris captured on the 20 micron filter states that they observed heavy amounts of Fe laminar, sliding and gear wear. The EDXRF-FDA method agrees that there are heavy amounts of Fe wear particles represented by the Fe-3P and Fe-4T levels. The CF Trenton filter analysis did not observe the Ag present on the filter. The presence of Fe can be attributed to the Accessory Gearbox, Fan, High Pressure Compressor, High Pressure Turbine and Low Pressure Turbine. The EDXRF-FDA method offers sources for the elements whereas the CF Trenton filter analysis method can not.

In the above examples, empirical agreement exists between the CF Trenton filter analysis method and the EDXRF-FDA method about the elements seen on a filter. However, differences between the methods will result because of the ability of the EDXRF-FDA method to discern the elements present in the particles on the filter. It can not be expected that microscopic observation of the color of particles alone is sufficiently sensitive to discern all the elements present on the filter. Several types of alloys have identical colors, i.e., Ag, Al, Mg, and increase the possibility of mistaking one type of alloy for the other unless lengthy, time consuming assays are done on each particle. Two elements, Ti and Ni, are not mentioned in any of the CF Trenton filter evaluations, but the EDXRF-FDA method definitely discerned significant levels of Ti and Ni in various samples. The observation of particles on filters by microscopic examination has advantages, but it is well beyond the scope of the method to be able to identify the elements composing the particles. The EDXRF-FDA method can discern the relative abundances of the elements composing the particles, assess the significance of the elements and indicate the possible sources of the wear in the engine based upon the combination of the elements from the metallurgy of the engine oil system.

The particles present on the 20 micron filters could not be easily analyzed by AES. Simply suspending the particles in oil would not suffice for AES analysis. The particles can be dissolved by strong acids and can be analyzed by Atomic Absorption.[2] Atomic Absorption was phased out of the DoD oil analysis program as a field instrument and is not used in the field in the CF. The particles can be dissolved by strong acids and resuspended in a medium suitable for analysis by AES, e.g., mineral oil.[10] This

procedure for using AES to measure particulate debris from F404 engine oil filters was deemed unsuitable for use in the field by CF military personnel.[1]

Conclusions: In the DoD and CF, F404 engine oil filters are changed every 200 hours. The oil filter that is removed is simply discarded. The analysis of debris from in-line oil filters yields a cumulative history of the wear the engine is experiencing. The EDXRF-FDA method described in this paper yields the relative abundances of each element, builds a database, statistically analyzes the database and sets limits based upon the database.

The other methods AES, particle counting and ferrography depend upon frequent grab samples to detect the particles that will indicate the onset of abnormal wear and/or failure. The grab sample only indicates the condition of the machine when the sample is taken. The frequency of sampling is dictated by the types of failures that are occurring in the machine. In the case of AES, it is assumed that the failure modes will generate sufficient quantities of particles in the size range that AES can detect within the frequency of sampling. This is why sampling for AES analysis requires small intervals between samples and the sampling frequency must be high.

Fine filters severely limit the use of AES, particle counting and conventional ferrography to monitor the wear condition of the machine. Numerous weapon systems have been removed from AES monitoring because of fine filtration and the inability of AES to detect abnormal wear and/or failures in weapon systems. In the case of the F404 engine, the effective ultra fine filtration of the engine oil system eliminates the use of AES in monitoring the wear condition of the machine. Monitoring of the wear condition of the F404 engine oil system is relegated to magnetic chip detectors and replacement of components/modules in the lubricant system based upon the hours of operation. However, F404 engines still experience failures. The EDXRF-FDA method represents the condition monitoring capability required to detect the onset of abnormal wear and the onset of failure modes in the F404 engine.

The EDXRF-FDA method is a common sense approach to monitoring the wear condition of the F404 engine and would give the DOD and CF a cutting edge, nondestructive technology that field personnel can easily use. The long lead times given by the EDXRF-FDA method before a failure occurs would allow for a significant reduction in the frequency of sampling a machine. Typically, for a jet turbine engine an oil sample is taken every 10 operating hours. For example, if the engine oil filter for the EDXRF-FDA method is taken every 200 operating hours then 20 oil samples would have to be taken in the same interval. In this example, the EDXRF-FDA method offers a reduction of 19 samples.

The DFDA machine demonstrates great potential in automating the preparation of samples for EDXRF analysis. However, more F404 engine oil filters need to be cleaned and analyzed by the EDXRF-FDA method to demonstrate the potential application to the EDXRF-FDA condition monitoring process.

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The Path to Affordable Long Term Failure Warning: The XRF-Wear Monitor

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Abstract: Long term early warning of wear related failure has recently been demonstrated for operational turbine engines. Particles recovered from Navy F/A-18 engine oil filters were analyzed for chemical elemental content using X-ray fluorescence analysis (XRF). [1] The data were compared with known engine metallurgy to determine the source of particles generated by wear, corrosion, and contamination. The identified sources agreed with engine history as recorded in the maintenance database. Normally operating engines showed low levels of wear particulates, as expected. The XRF filter debris analysis method (XRF-FDA) successfully identified every oil wetted wear-related failure as having elevated quantities of metals. Warning times in excess of 100 operating hours [2] were achieved through the ability of XRF to measure elements other than iron. Some engines undergoing high time replacements showed high levels of metals as expected; the method enables the low wear engines to be identified. These striking results have implications for planning of operations and maintenance. This paper presents the XRF-Wear concept for autonomous on-line monitoring of aviation engines and other high value machinery. An economically advantageous approach to assembling the wear-profile database of previously unmonitored equipment is offered in the context of a fully automated, field deployable, on-site expert system.

Keywords: wear, debris, particle, filter, wear source, corrosion, warning, X ray, XRF, fluorescence

Introduction: Wear related failures of high-value combat systems may be avoided through a knowledge of the wear condition of the individual weapon system. For numerous weapon platforms with advanced fine (3 micrometer) filtration, there are effectively no remaining wear-metal particulates for traditional spectroscopic oil analysis to detect, and maintenance becomes schedule-based rather than condition-based. [3]

Recent advances in machinery monitoring technology, discussed in this paper, have demonstrated the ability to forecast wear-related failures over 100 operating hours in advance for the F404 engine in F/A-18 aircraft. The method involves removing suspended particles from the circulating oil and analyzing their constituent chemical elements by X-ray fluorescence (XRF). Before proceeding to a discussion of the XRF monitoring method used in this study, we will briefly discuss the physical basis for the method, and related work by others.

The X-Ray Fluorescence Method: When an individual atom is missing an electron from an electron orbit, one of the electrons in an orbit further from the nucleus may fall into the vacancy and release its excess energy as a photon. The energy difference between the two electron orbits goes into the emitted photon. For inner shell orbits, the energy difference is large, and the emitted photon is a penetrating X ray. The exact amount of energy given to the photon is characteristic of the emitting atom. X-ray detectors can measure the photon energy, the value of which serves as a fingerprint of the emitting atom. Thus, a spectral measurement of the number of photons at each energy leads to a determination of which chemical elements are in the sample and in what quantities. Characteristic X rays may be produced in various ways, e.g. by electrons bombarding the metal target of an X-ray tube. The non-destructive X-ray analysis performed in the scanning electron microscope (SEM), performed for example in conjunction with ferrographic analysis, also uses these same characteristic X rays produced by electron bombardment. The characteristic X rays are called fluorescent X rays when the atomic vacancies are generated by incoming "primary" X rays, for example those emitted by an X-ray tube. Fluorescence refers to immediate photon emission in response to an absorbed incoming photon.

In the basic physical emission process, XRF spectroscopy is conceptually parallel to the well known atomic emission spectroscopy (AES). Of course, they differ in the way in which the electron vacancies are produced, but both involve electron transitions between bound orbits. For XRF, these transitions are between inner shells close to the nucleus, whereas for AES the transitions are between outer shells. This basic distinction leads to significant differences in technology and capability. The two methods are compared in Table I. Both methods can analyze all the essential structural metals whether produced by wear or by corrosion, as well as silicon (dirt), and are not limited to magnetic materials.

XRF is capable of measuring fine particles as well as plate metal samples. However, it is limited by the depth from which the X rays are capable of exiting the sample. Thus, a plate metal sample which is half an inch thick will give the same readings as a thicker sample of identical composition. This leads to a particle size effect, despite which XRF still produces large signals for large particles and small signals for small particles. The sensitivity to small particles, where X-ray absorption is negligible, is enhanced relative to thick samples. Compared to the well known particle size limitations of AES, which prevents measurements on particles larger than ~10 micrometers in size, [4] the XRF particle size effect is rather mild. Thus, the XRF method measures particles of all sizes.

XRF is a very sensitive technique. XRF can readily measure and identify the small amount of elemental metal in several atomic layers of an area one centimeter square. [5] This is a small thickness even when compared with normal machining tolerances of individual components.

TABLE I	OPTICAL	X-RAY
Spectroscopy:	AES, AAS	XRF, SEM-EDX
Orbital Electrons:	Outer Shell	Inner Shell
Photon Energy:	~1 eV	~1000-100,000 eV
Elemental ID:	Characteristic Lines	Characteristic Lines
Compositional Effects:	Interelement or Matrix Effect	Matrix Effect
Calibration:	Fluid standards (Relative)	Calculational or solid standards (Absolute or Relative)
Sample:	Fluid, fine ($\leq 10\ \mu m$) particle suspension	Fluid, solid, suspension (any size)
Science:	Mature	Mature
Technology:	COTS, lab, field	COTS, lab, field, On-line process monitoring

The capability to quantitatively determine the elemental content of the sample from X-ray fluorescence (XRF) measurements was developed at the Naval Research Laboratory and put into the public domain in the 1960s and 1970s. [6] NRL produced the first XRF spectrometer with electronic detection, multichannel analysis of energy dispersive XRF detectors, and public domain software for quantitative analysis, a combination whose legacy endures in today's commercial XRF instrumentation. The NRLXRF computer program incorporated fundamental parameters as well as empirical coefficient methods and treatment of particle size effects into one cohesive and flexible package.

Earlier XRF Work on Wear Particles: The utility of XRF for analyzing metallic content in organic fluids has been recognized for a long time, [7] and has become the basis of the fingerprinting of oil sources, the on-line process control of fuel oils for sulphur content, and the commercial availability of instrumentation for such purposes. In addition to its use on organometallics and dissolved metals, XRF has been applied to suspended metal particulates in oil lubrication systems. [8] On-line XRF monitors have been developed with the goal of sensing Fe concentrations in the parts per million range necessary for condition monitoring of turbine engines; [9] the instrumentation then available was found unsuitable for use on an operating engine. Several reports demonstrate the superiority of XRF over atomic spectroscopy for detecting failure modes involving large particles. In one specific case, a failure went undetected by properly performed atomic spectroscopy, but would have been detected in advance had XRF been used, as verified subsequently from the archived oil samples; in this study, XRF agreed closely with more laborious but highly reliable wet chemical analysis methods. [10] A study of Sea King helicopter engines was carried out on suspended particulates in drawn oil samples by Veinot, who concluded that XRF warned of an oncoming failure one sampling period (~15 operating hours) earlier than atomic spectroscopy. [11] Note that even when the particulates remain in the oil, XRF can offer improved warning time.

Other workers have made use of drawn oil samples of a few milliliters, from which they filtered the particulates for presentation to an XRF instrument. By removing the oil from the particulate sample, both the X-ray scattering and the X-ray absorption by the oil are avoided, the sample is concentrated, and metal detection limits are improved. While Fe and higher atomic numbers can be analyzed suspended in the oil, light elements like Mg, Al, and Si require the oil to be

removed. Meier, et al., [12] filtered drawn samples from a bearing on a test stand and performed XRF analysis on them: a pitted bearing produced little Fe (below 1 microgram/hour) during about 100 hours of operation without load, but the wear rate immediately increased 2 orders when the load was applied. This work demonstrates that the sensitivity of XRF is sufficient even to observe changes in operating conditions of a single bearing experiencing advanced wear.

These examples of XRF analysis of wear particulates all assume that the particulates are present in the circulating oil. The same assumption is made by the spectroscopic oil analysis program (SOAP) for monitoring the condition of major machinery in the DoD. For numerous modern machines with fine filtration, this assumption no longer holds: the particulates are essentially all collected in the system's canister oil filter. Fine filtration extends machine life, but removes the ability to ascertain the end of that life using SOAP or other methods relying on the presence of suspended particulates in drawn oil samples. At present, many such systems are maintained on a scheduled basis rather than by condition monitoring. However, by examining the particulates concentrated in the canister filter, considerable insight into the machine condition can be achieved.

The JOAP-TSC Study of F404 Filters, Procedure: The Joint Oil Analysis Technical Support Center (JOAP-TSC) conducted a study [1] of engine oil filters collected from the F404 engines of operational F/A-18 aircraft. Although the filter, when new, passes particles in the size range which SOAP can detect, it effectively becomes a fine filter in use as deposits accumulate and entrap particles as small as 3 micrometers or less. The filters were pulled by the mechanics at the normal interval of 200 operating hours. There was no requirement to collect multiple filters from individual engines. Each filter was assigned a reference number to enable tracking and sent to the JOAP-TSC for analysis. Particulates were recovered from each filter individually by immersing in a fluid bath and sonicating for 5 minutes. The released particles were collected on a membrane filter patch, fixed in place with a polymer, and presented to the XRF instrument, a commercially available Spectrace 6000. The XRF unit automatically pumps down to vacuum and carries out a measurement protocol to determine 18 pre-selected elements in the sample. (The elements were Al, Ag, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Si, Sn, Ta, Ti, V, W, and Zn.) The entire procedure is complete in 20 minutes for a single filter, which can be reduced to an average of 15 minutes per filter when processing several in succession. The values reported by the XRF analysis were entered into a database with a separate record for each of the 189 filters analyzed. The data for an individual element were analyzed and each was assigned an index value corresponding to a five level statistical ranking of the distribution for that element. Level 1 included data within one standard deviation from the mean; higher levels had successively larger quantities of the element. These results were then compared with the metallurgy of engine components. A decision tree was constructed by which the engine module containing the failed component would be called out. These wear source identifications were made at the module level, to enable comparison with the entries recorded by the mechanics in the Aircraft Engine Maintenance System (AEMS) database. The AEMS database includes information such as the time on the engine, serial numbers, which module was maintained and when, and whether the engine had experienced a failure or was operating normally. The identity of the individual failed part is generally not available.

The JOAP-TSC Study, Results:

Since wear particle monitors historically have functioned as critical failure warning devices, the results were examined for engines which had suffered a failure of oil-wetted parts. Filters from

corresponding filter showed elevated quantities of a major metal. In addition, the metals found in the filters were the metals to be expected from the module which had failed.

A detailed example will illustrate the utility of the method. Two oil filters were taken from engine serial number 310810. Oil filter number 1 was removed from the F18 engine at 2548 hours since new (HSN). XRF found Ti, Mo and V at Level 2, and Co at Level 3. The Ti and V indicate a Ti 6-4 alloy and the Co and Mo indicate tribaloy coating. This combination of elements, Ti, V, Co and Mo, can originate from the Fan and High Pressure Compressor (HPC) modules. When the second engine oil filter was removed 239 hours later (2787 HSN), Cd showed up at Level 2, V at Level 4, and Fe at Level 5. The Fe with V indicates abnormal bearing wear. This combination of metals, Fe, V and Cd , can originate from the HPC and also from the Low Pressure Turbine. Notice the radical change in the elements and their significance levels by the time the second sample was taken. Thirteen hours after the second filter was taken (2800 HSN), this engine experienced HPC failure. The elements in both samples indicated the HPC was a source of these elements. The XRF filter debris analysis technique indicated a problem 252 operating hours before the High Pressure Compressor failed. At 13 operating hours prior to the failure, the XRF technique indicated a bearing failure was in progress.

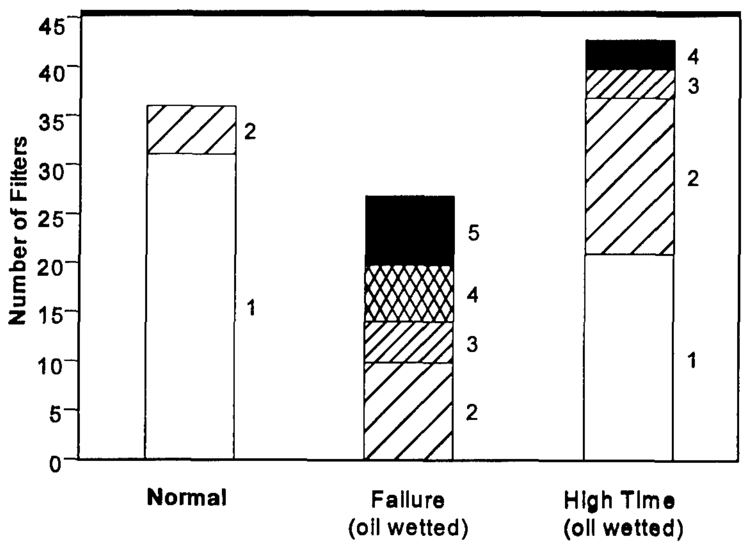

Figure 1. XRF analysis of filters for normal engines, failed engines, and engines at high time replacements. Increased levels of the three major metals (Fe, Ni, Ti) are assigned higher index values (indicated to the right of the bar). Most of the normal engines showed Level 1, while about 15% showed Level 2. None of the failed engines showed Level 1. High time engines clearly showed advanced wear in some cases (Levels 3 and 4), and low wear in others.

In addition to its long-term early warning capabilities, the XRF method can detect dirt contamination as well as corrosion and indicate where corrosion is occurring.

A wear monitor should also be able to correctly identify a normal engine, one which is not

experiencing abnormal wear. Approximately 85% of the normally operating engines (as so identified by the mechanics) exhibited metal levels within one standard deviation from the mean (Level 1) for the three major metals, as depicted in Fig. 1. The remaining normal engines had Level 2 for at least one of the major metals, but none showed any higher level. It is not known whether these Level 2 engines were entering into otherwise undiagnosed abnormal wear, but it is quite clear that the Level 1 engines were in fact in good wear condition, in agreement with the mechanics' assessments.

Figure 1 also reports the data recovered from engines which had undergone scheduled replacement of oil wetted parts due to the high amount of operating time they had experienced. In the absence of an effective condition monitoring technology, replacement schedules must be sufficiently conservative to prevent failures. The high-time data in Figure 1 clearly show that a significant fraction of the engines were in fact experiencing advanced wear, and were putting out Level 3 and Level 4 of the major metals. The schedule of replacements has been set to catch these engines prior to failure. However, the statistics of the process are such that nearly half of the replacements were for parts still operating at the low Level 1. That is, many of the replacements were carried out on normally operating parts. It is not known how much longer these normal engines would have continued with low levels of wear metal production; however, the availability of the XRF monitoring technology puts that finding within reach.

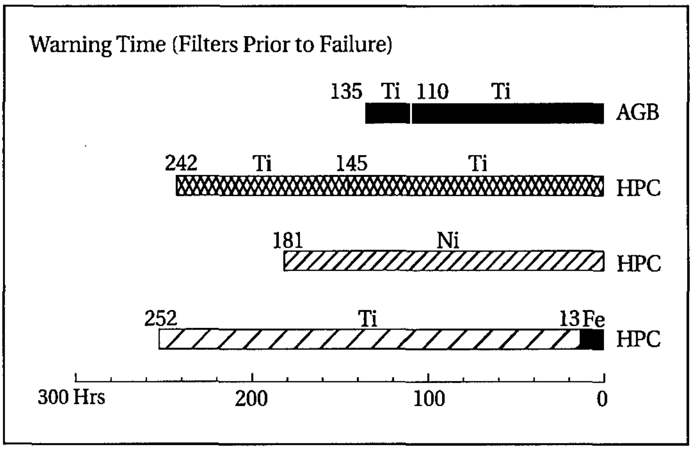

Figure 2. Filters pulled prior to failure showed long term early warning. The Levels are plotted with the same hatching as in Fig. 1. Numbers above the bars indicate hours prior to failure. Acronym (right) is the module which failed, also identified by XRF analysis. (AGB = Accessory Gear Box). High level metal is identified by chemical symbol.

Some filters were pulled because a failure had occurred. Others were pulled prior to a failure and showed high levels of wear metals. The data from these filters are presented in Fig. 2 as a function of time before failure. Note the remarkable time scale, extending out to hundreds of hours, well beyond the time scale of previous monitoring methods. In most cases, the high level metals were Ti or Ni. In other words, attainment of long-term early warning for the F404 is contingent upon elemental analysis of *nonferrous* alloys . Magnetic plugs or chip detectors would not have captured these alloys or indicated their presence. The XRF analysis also identified the engine

modules which later failed.

Management Implications: The implications of these capabilities for maintenance management are straightforward and important. [?] An individual machine which is unexpectedly nearing the end of its wear life can be identified and overhauled, whereas a machine which is unexpectedly *not* experiencing advanced wear can be left in service. This is the essence of condition based maintenance. The XRF method allows these decisions to be made on an individual machine basis, rather than on the basis of the statistics of a large number of machines. By insuring the timely repair of worn machines, secondary damage will be reduced. By extending the service of individual non-wearing machines, the average life of the population of monitored engines will be extended and the consumption of replacement parts reduced.

The availability of a long term failure warning technology also has implications for operations management. Here, it is important to identify the normally operating engines, and to commission these for deployment, thus avoiding the high cost of breakdown in remote locations or during mission critical operations.

The XRF-Wear Concept: The above benefits may be accrued by implementing the XRF-Wear concept for monitoring with a higher degree of automation than is currently available (see Table II). The XRF-Wear concept builds upon the three fundamental advantages of XRF filter debris analysis as a condition monitoring method: (1) the ability to measure particles of all sizes and alloy compositions, (2) the high sensitivity and wide dynamic range of XRF, and (3) collecting the sample from the full oil volume. The XRF-Wear concept is directed toward both on-site and on-line automated expert systems.

TABLE II **XRF-Wear Automation**	**Manual XRF** (today)	**XRF-Wear** (future)	
		On- Site	On- Line
Debris Collection			X
Debris Retrieval		X	X
Sample Prep/ Presentation		X	X
Sample Analysis	X	X	X
Action Limits/ Guidelines		X	X
Reporting		X	X
Multi- canister robot		(X)	

The on-line system will be able to monitor a single high value machine throughout its wear life, and automatically provide reports, maintenance warnings and condition assessment along the way. For use on board a manned ship or at a land facility with multiple machines, a design with a socket-mounted sensor head permits a single sensor to be manually moved from one machine to another as needed. For aviation, the system may be configured to issue an XRF-CBM squawk upon landing; in-flight warning could be provided, if required. Similar capabilities are envisioned for non-aviation applications. Remote operation with satellite links is one very real option; another is untended, autonomous operation for reduced manning situations on ship or shore.

The principal advantage of on-line monitors, namely the ability to protect a single vehicle or machine, is also its limitation. For the monitor to be able to issue warnings, it must have limits set for issuing those warnings. Setting the limits is an engineering function performed on the basis of

an accumulated database containing data on the wear profile of the engine type being monitored. Thus, accumulating the wear profile database becomes an essential prerequisite for effective monitoring. Using on-line monitors alone, that database can only be filled by accumulating the data produced by the monitors themselves. A statistically meaningful number of monitors must be installed on a statistically meaningful number of machines. During the initial period while the database is being established, the monitor cannot issue reliable warnings. Also, on-line monitors must be retrofitted onto each machine, or designed into a new system; either of these processes consumes calendar time.

A much more economical and immediate approach to accumulating the database is achieved with the on-site system. The process of collecting engine filters from a population of operational machines can begin immediately, even before the on-site system is either designed or built. Once built, the on-site system may be robotized to automatically process a rack of filters, without tending by an operator. The operator need only load a quantity of filters in the morning (each with its own identification or bar code), start the process, return at the end of the work shift to verify completion, unload the processed filters, and start another batch. Within a few days, an entire database can be accumulated for a new engine type which previously had not been monitored. Once the database is in hand, monitoring may proceed either with on-line monitors or by analyzing filters on-site.

The on-site system can also be supplied in a form suitable for smaller scale operations not requiring batch processing, in which individual filters are manually mounted and thereafter automatically processed. The throughput of such a system would still be substantial, since the operator is freed from tending the operation. This model of the on-site monitor is well suited to flight line, shipboard, laboratory, or installation usage. Using commercially available components, the system may be configured to automatically transmit the collected data to a central engineering database, to a management database, through an integrated local network such as the Integrated Condition Assessment System (ICAS), or to multiple destinations.

The on-site approach to filter debris analysis may be sufficient for many weapons platforms. With the long term early warning available with XRF-FDA, even a central filter analysis site (serving a large geographical area) may be effective in some cases. On-site filter debris analysis requires no retrofit, no additional poundage on board an aircraft, and no change in current practice other than to collect the filters. The on-site monitor may be used to analyze filters pulled at the normal cycles. In some cases, it may be cost effective to modify the filter changing period to insure sufficient warning time. Depending on the individual situation, this may be longer or shorter than the 200 hour period now in use with the F404 engine. For example, analyzing a filter just prior to a scheduled parts replacement may indicate or contraindicate the need for carrying out the replacement when initially scheduled. On the other hand, the occurrence of a chip detection event will almost certainly merit analysis of the filter debris; this analysis may be highly automated with the on-site monitor.

Implementing the XRF-Wear Concept: The state of current technology is ready for implementing the XRF-Wear concept. The power requirements of the system are modest. NRL has pioneered the application of computers to the analysis of X-ray fluorescence data, which now requires no more computational power than an Intel 80286 processor. XRF is miniaturizable. NRL has built an XRF system to fit within a 1.25 inch diameter pipe, and used it for environmental monitoring of subsurface soils. [13] The components in such a system employ technologies already present in flight systems. Automated filter debris recovery has been demonstrated with the Deployable Filter Debris Analyzer (DFDA) developed for the Canadian Department of National

Defence (DND) by GasTOPS Ltd. Individual filter canisters are mounted on the analyzer, and the particulates are then washed out, sized, and collected on filter patches. [14] The XRF-Wear concept may be implemented by extending the capabilities of the DFDA to include X-ray fluorescence analysis to achieve an on-site analysis station. Addition of rack mounting of filter canisters will enable the rapid accumulation of a wear profile database.

Summary: XRF-FDA is an effective technology for analyzing particulate contaminants in oil lubrication systems. The development of the XRF-Wear concept will enhance the ability of management to plan both maintenance and operations. XRF-Wear complements current trends toward fine filtration, longer life cycles, lower labor costs, and reduction of unnecessary replacements, while offering a path toward affordable readiness through condition based maintenance. The XRF debris analysis method is applicable to a wide variety of rotating and reciprocating machinery and fluids.

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Scintillation Method of Analysis for Determination of Properties of Wear Particles in Lubricating Oils

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Abstract: Nowaday there is a demand for effective methods and equipment for early detection of failures of aircraft engines. The spectral diagnostics methods used in Russian civil aviation have a low information capacity and poor metrological features and they can not be used for reliable prognosis of the engine serviceability. Applied Physics Institute of Irkutsk State University (Russia) together with Joint-Stock Company «Baikal Airlines» have elaborated the scintillation method of analysis of lubricating oils for wear products. It enables to obtain quickly and with high accuracy the information on

- a metal wear particles content,
- a dissolved metal content,
- an amount of wear particles,
- an amount of simple particles,
- an amount of complex particles,
- a composition of each particle.

The exact determination of wear particle composition (including micron-sized particles of Fe-Cu, Fe-Ni, Fe-Ag) permits to pursue the unit-to-unit diagnostics of aircraft engines.
In addition to the civil aviation the scintillation method is applicable for diagnostics of an equipments in airforce, a navy, a petroleum and engineering industries, in automobile, railway and sea transport and other engines and mashines. Besides, this method may be useful for tribological investigation of a quality of lubricant materials, in the development of new lubricants.

Key words: Aircraft engine; ferrograghic analysis; graduation; lubricating oils; metrological properties; scintillation spectral analysis; spectrometer; unit-to-unit diagnostics; wear particles.

Introduction: In accordance to data of Rolls-Royce Company 50 per cents of mechanical faults of aircraft engines are being detected with the use of tribological methods [1]. By the tribodiagnostics is meant techniques of continuous measurements of a content and a number of ferromagnetic particles with the use of on-line sensors and, in addition, the methods of periodical off-line measurements. However the sensors can come into false action and incorrect conclusions may be done on oil fitness. For instance, the sensors ODDS (in accordance to Tedeco Vickers) give 30 % of false actions.

The method of periodical laboratory checks are more time consuming, but they enable to predict exactly the work features of an engine.

Among the laboratory methods the ferrographic and emission spectral techniques can be called first of all, which provide a great body of data on wear particle. Now a loss of interest in emission spectral methods should be noted. It is associated with that the serviceability of an engine can be judged from the value of content of wear particles. Since the element content is measured with a low accuracy and depends on many random parameters, the efficacy of this method is insufficient [2]. Nevertheless so far emission spectrometers have being produced by the firm Baird for Defense Department of USA [3], and emission spectral method is one of the main techniques for failure prediction in Russia.
Ferrographic method gives the maximum of information on wear products- the size of particles, its shape, the metal content and the alloy type. But it is very time consuming and in many cases does not give the opportunity of material identification. A low resolution in process of alloy determination (for instance, iron alloy with a different content of chrome) limits the possibilities of unit-to-unit diagnostics. The problem is also the correct determination of admissible values of wear particles features.

From the above it is clear that the modern diagnostics equipment has a number of disadvantages reducing the efficacy of its use. Some of them (determination of a particle size by on-line sensors) are of fundamental nature and can not be eliminated in the frames of these methods.

The simultaneous application of the ferrographic and emission spectral methods can give the required information on wear products in oil. Such set of equipment is used in the service center of the airport «Sheremetievo». But the price of this equipment is about $400 000 and small aircraft companies can not afford to buy it. Hence the elaboration of new not expensive methods providing maximum of information about wear particles is vital now.

One of such methods is a scintillation method of analysis [4] based on serial inputting of wear particles in the area of spectrum excitation and detection of radiation signals from these particles. Let us remember the principle of its operation. (the figure 1).

The principle of scintillation spectrometer operation: The preliminary prepared sample is spraying by the special ultra-sonic sprayer (1). Obtained spray consisting of oil droplets and wear metal particles is blowing in plasma of a UHF-discharge (2) by the gas stream. The temperature of plasma is 5200 K. The sprayer works so that wear particles resided in oils go into plasma sequentially one by one. When a particle fell in plasma it is heated, evaporated and the atomic vapor obtained is excited. A flash (a scintillation) of a particle occurs.

A condenser (3) focuses the radiation onto a spectral device (4). The polychromator (4) resolves the radiation spectrum that is detected by the photomultipliers (5-7). The duration of a radiation pulse of a particle is proportional to the duration of its stay on plasma and comprises 1-10 ms, the amplitude (the area of a pulse) is proportional to the evaporated mass of a particle. Thus there is a sequence of pulses with different amplitude and a

different duration on the output of photomultipliers. Electrical pulses come from them into the analog-digital converter (8) and are treated by the computer. The pulse signal corresponds to wear particles, a continuous signal is bound with dissolved metal.

The figure 1 shows only three channels to pick out the signals. Its number depends on a type of polychromator and may be increased. Each channel is tuned to the detection of the spectral lines of given element.

As simple particle, consisting only one element, enter the plasma (for example, iron particle), a sequence of radiation pulses is present only at one channel (the channel 5 in the figure 1(b)). At the channels 6 and 7 a continuous weak background radiation of plasma is observed.
In the case when complex metal particles, consisting of some elements and simple particles reside simultaneously in oil the computer analyzed the times of a signals appearance.

If two or more pulses agree in time it points to a complex composition of the particle. In the figure 1 (b) pulses coincident with each other in time at the channels for Fe and Mn are shown.

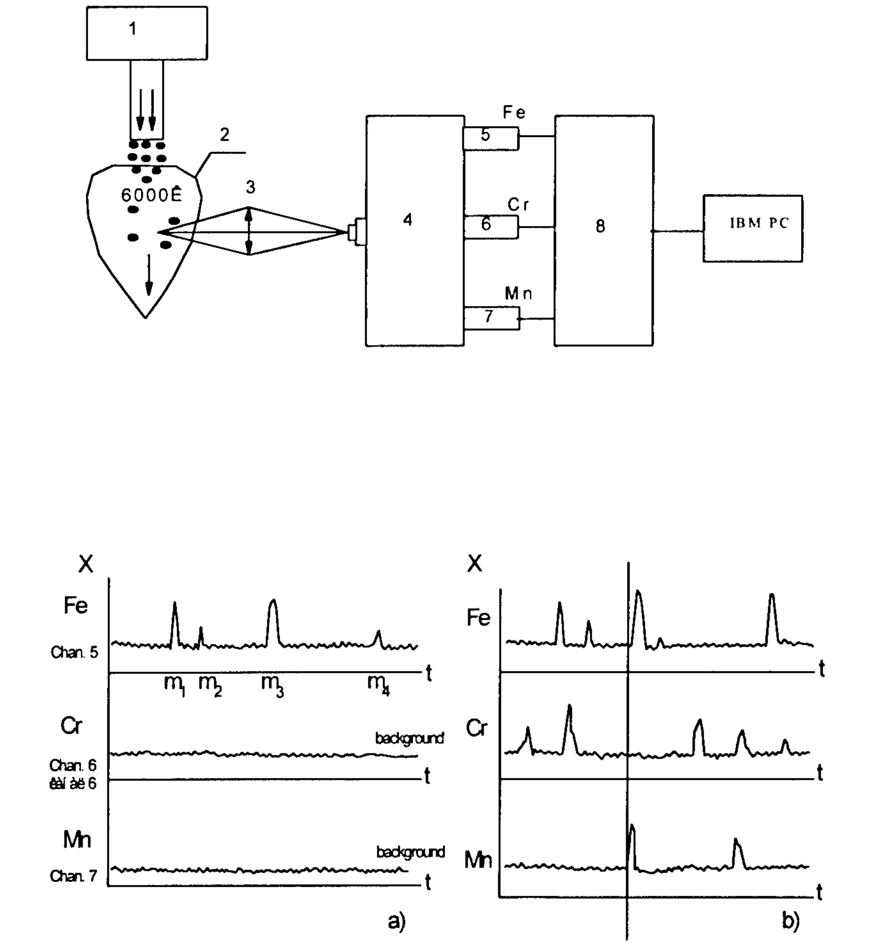

Figure 1. The sketch of scintillation spectrometer for three channels. The sequence of radiation pulses a) for one element being determined, b) for three elements

The standard deviation for determination of a stechiometric composition S was evaluated on reference particles, specially prepared, with known composition. It was less than 0.25. Hence it follows that dependence of scintillation signal on particle path does not play a decisive role.

Results on particle composition were compared with those obtained on microanalyzer Camebax SX-50. They agree very closely.

Thus from the above it is seen that the scintillation method provides the possibility within 5 minutes to obtain the information about:

- a metal wear particles content,
- a dissolved metal content,
- an amount of wear particles,
- an amount of simple particles,
- an amount of complex particles,
- a composition of each particle.

It should be added that stabilization of a discharge in UHF plasma generator the air was used supplied through the special filter. The use of air reduces the metrological properties of the method, but it saves the operators the trouble and expense of using argon and nitrogen. The discharge chamber of plasma generator can work without failures during 1000 hours.

The graduation of the scintillation spectrometer when both continuous and pulse signals are detected: For graduation of scintillation spectrometer the following system of equation are used:

$$\begin{aligned} \overline{F} &= a_1 + a_2\left(C_L + C_P^1\right) \\ B &= b_2 \cdot C_P^2 \\ C_P &= C_P^1 + C_P^2 \end{aligned} \tag{1}$$

where $\overline{F}$ - is continuous signal, B- is a pulse signal, $\tilde{N}^1{}_D$ is the content submicron-sized impurities, $\tilde{N}^2{}_D$ is the content of large particles, $\tilde{N}_L$ is the content of dissolved metal.

We assume here that:

- dissolved metal does not provide scintillation pulses
- submicron-sized particles, for which the scintillation principle breaks down (that is the analytical area has more than one particle), gives rise to the spectrum background, similar to dissolved metal,
- large pulses do not effect a background component of a signal, and a small pulses do not give a contribution in the pulse component. Thus a content of wear particles is split into two components $\tilde{N}^1{}_D$ and $\tilde{N}^2{}_D$, the sum of which results in the total metal content.

To obtain the graduation curve the three coefficients must be defined: a_1, a_2 b_2. It may be done in two stages:

1. To find the parameters a_1 and a_2 the standard samples are used, which have only dissolved metal (the standard Conostan). In this case $\tilde{N}^1{}_D$ =0 and graduation procedure involves the solution of the equation

$$\overline{F} = a_1 + a_2 \cdot C_L \tag{2}$$

2. To find the parameters $\tilde{N}^1{}_D$ and $\tilde{N}^2{}_D$ the standard samples are used, which have only discrete impurities. From eq.(2) the content of submicron-sized particles is determined as

$$C_P^1 = \frac{\overline{F} - a_1}{a_2} \tag{3}$$

and the content of metal in large particles

$$C_P^2 = C_P - \frac{\overline{F} - a_1}{a_2} \tag{4}$$

After this the regression dependence for analytical parameters B is constructed as:

$$B = b_2 \cdot \left(C_P - \frac{\overline{F} - a_1}{a_2} \right) \tag{5}$$

The limit of detection and reproducibility of the method: The apparatus had two channels tuned on the spectral lines FeI 302.0 nm and CuI 324.3 nm. The flashes of these spectral lines were detected. In doing so, we detected a number of scintillation pulses N (a number of particles detected) and the total area S of pulses was measured. The both values were used as the parameters associated with the content of elements in oil.

The goal of the experiment was the evaluation of accuracy and limits of detection of metal in oil. For this purpose the reference samples were prepared where wear particles were simulated by the oxide power Fe_2O_3 and Cu_2O [5]. As the base the oils MGD-D, MS-8P, SM-4.5 and B3-V were taken.

The use of different oil bases enables to evaluate the influence of oil type on a signal level. As analytical parameter the average X over 20 separate measurements, with excluding the gross errors, was taken.

The graduation curve has been constructed for all types of oil (the table I).

Table I

The content of Cu and Fe in "clean" oils C_{idle}

Type of oil	The content of metal C_{idle}, µg/g	
	Cu	Fe
MGD-D	0,4	0,9
MS-8P	0,3	1,4
SM-4.5	0,1	0,3
B3-V	0,1	0,7

The confidence interval $\Delta C = \pm 2\sigma_{\hat{A}}/C$ in working span of contents was calculated for a single measurement at reliability P=0.95 in accordance with [2]. The value of standard deviation σ_C of a single measurement was gained from the standard deviation of separate measurements of signal level on graduation plot $\sigma_{\tilde{O}}$. The value ΔC for all the types of oils was approximately the same. The table II lists the averaged values for ΔC.

Table II

The confidence interval for single measurement of metals content by the scintillation method

Cu	C,μg/g	1	2	3	4	5	
	ΔC, (%)	17	14	12	16	17	ΔC, (%)=15
Fe	C,μg/g	2	4	6	8	10	
	ΔC, (%)	30	30	35	30	35	ΔC, (%)=32

This value remains practically constant with a change of the metal content. It provides reason to take the mean value ΔC as a constant in whole range of contents being determined and for all oils.

The value m_{min} may be thought of as limit of detection in working spans of contents (the table III), according to [6].

Table III

The value m_{min} for the scintillation method of analysis

Oil		Cu			Fe		
Oil	Parameter	C_{idle}, μg/g	V_{const}	m_{min}, μg/g	C_{idle}, μg/g	V_{const}	m_{min}, μg/g
MGD-D (O1)	N		0,06	0,1		0,13	0,7
		0.4			0.9		
	S		0.06	0.1		**	-
MS-8P(O2)	N		0,03	0,04		0,11	0,8
		0.3			1.4		
	S		0.03	0.04		**	-
CM-4.5(O3)	N		0,04	0,02		0,14	0,3
		0.1			0.3		
	S		0.06	0.03		0.14	0.3
B3-V(O4)	N		0,06	0,03		0,08	0,3
		0.1			0.7		
	S		0.06	0.03		0.13	0.5

The average from O1 to O4: $\overline{m}_{\min Cu} = 0.05$ μg/g, $\overline{m}_{\min Fe} = 0.5$ μg/g.

Thus, the accuracy of the scintillation method complies fully with requirements in [5]. Results have been obtained on the laboratory model of the scintillation spectrometer. After advancement of the apparatus and instructional materials the accuracy may be notably enhanced.

Unit-to-unit diagnostics of aircraft engines on scintillation measurements: To localize the failure the data from the bill of parts and units of aircraft engines had been used. The bill listed the information on parts and units working in oil, a mark of material and chemical composition of material.

Table IV gives indications that have been obtained from chemical composition of materials and combined on units. As it is seen from the table IV the engine is divided into 7 units.

The name of wear indication, for example Fe (Cr11Ni10), points to basis element of alloy, alloying elements and their percentage are given in brackets. In doing so, the alloying elements are taken into account, the content of which is sufficiently large and detection of which in wear products is most probable.

The indication on wear hardening particles is listed separately. Such particles may arise by interaction of engine parts with the different composition or different composition of coating. The presence in oil of wears particles of definite wear indication or the group of wears indication points to wear of corresponding parts and units.

Thus, the presence of particles of Fe(W9), Cu(Zn34), Al(Cu5), exceeding some limit values in the content and in the number, is indicative of an intensive wear of bearings, and particles of Ti and Mg(Al9) testifies to a failure of a starter.

The situation is possible when particles Fe(Cr12) are detected, which may belong to may units of engine. In this case the particles of hardenings should be taken into account. If, for instance, together with Fe(Cr12) there are particles TiAl then more likely the defective unit as is a compressor.

Table IV
Characteristic indications of engine parts wear

On material composition							
	Engine units						
Material	Starter	Bearings	Transmission	Compressor	Separator body and drives body	Turbine	Oil units
Fe	o*	o*	o*	*	*		*
Fe(Cr12)	*		*	*	*	*	*
Fe(Cr19)					*		
Fe(Cr11 Ni10)	*		*		*		
Fe(W9)		o*					
Cu(Zn34)		*					
Cu(Zn6)	*						
Cu(Pb27)							*
Cu(Sn7)	*						
Cu(Al11)		o*					
Al				*			
Al(Cu5)		o*					
Mg							*
Mg(Al 9)	*						
Ti	o*						
Ag		*					
On wear hardenings							
	(FeCu) (FeMg) (FeTi)	(FeCu) (FeAg) (CuAg) (FeAl)		(FeAl) (TiAl) (FeTi)			(FeMg) (FeCu)

The table V gives the results of scintillation measurements for wear particles in oil of an intact engine with the working time 3092 hours.

Table V

The results of scintillation measurements of properties of wear particles in oil of an intact engine. The time of its work is 3092 hours.

The work time is 3092. Oil Turbonicol	Fe					Cu				
	N	$C_d+\dot{N}_p$, µg/g	D, con	$\dot{N}_{atk}$	$\dot{N}_{aa}$	N	$C_d+\dot{N}_p$, µg/g	D, conv	$\dot{N}_{atk}$	$\dot{N}_{aa}$
	4	0 + 0.02	1.10	0.2	-	6	0.0+<0.01	4.0	0.1	-
	Number of complex particles					Number of complex particles				
	FeMg 0	FeCu 0	FeAg 0	FeNi 0	FeAl 0	CuMg 0	CuFe 0	CuAg 0	CuAl 0	CuNi 0
The pouring oil after the ferrograph study	6	0.02+0.16	1.2	-	-	37	0.0+0.01	3.2	-	-
	Number of complex particles					Number of complex particles				
	FeMg 2	FeCu 0	FeAg 0	FeNi 0	FeAl 0	CuMg 9	CuFe 0	CuAg 0	CuAl 0	CuNi 0

Ag					Al				
N	$C_d+\dot{N}_p$, µg/g	D, conv	$\dot{N}_{atk}$	$\dot{N}_{aa}$	N	$C_d+\dot{N}_p$, µg/g	D, conv	$\dot{N}_{atk}$	$\dot{N}_{aa}$
1	0.0+0.01	3.0	-	-	0	0	0	-	-
Number of complex particles					Number of complex particles				
AgFe 0	AgCu 0	AgAl 0	AgMg 0	AgNi 0	AlFe 0	AlCu 0	AlAg 0	AlNi 0	AlMg 0
0	0.0+0.0	0	-	-	2	0 + 0.01	0.15	-	-
Number of complex particles					Number of complex particles				
AgFe 0	AgCu 0	AgAl 0	AgMg 0	AgNi 0	AlFe 0	AlCu 0	AlAg 0	AlNi 0	AlMg 0

Ni					Mg				
N	$C_d+\dot{N}_p$, µg/g	D, conv	$\dot{N}_{atk}$	$\dot{N}_{aa}$	N	$C_d+\dot{N}_p$, µg/g	D, conv	$\dot{N}_{atk}$	$\dot{N}_{aa}$
0	0	0	-	-	23	0.00+0.01	0.8	-	-
Number of complex particles					Number of complex particles				
NiFe 0	NiCu 0	NiAg 0	NiAl 0	NiMg 0	MgFe 0	MgCu 0	MgAg 0	MgAl 0	MgNi 0
0	0.0+0.0	0	-	-	80	0.0+0.04	4.0	-	-
Number of complex particles					Number of complex particles				
NiFe 0	NiCu 0	NiAg 0	NiAl 0	NiMg 0	MgFe 2	MgCu 9	MgAg 0	MgAl 0	MgNi 0

Here: N is a number of pulses detected, which is proportional to a number of wear particles, C_d is the element content of dissolved metal and submicron-sized particles, C_p is

the element content of wear particles, D_{conv} is the parameter proportional to the mean size of particles, C_{aa} and C_{atk} are the total content of metal determined by the different methods.

Noteworthy is here a small number of detected particles of all elements, a low content of wear particles and almost full absence of complex particles.

The table VI contains the results of ferrographic and emission spectral analysis of the same engine, made in technical center of airport "Sheremetevo". Analysis did not reveal any disrepair in its work.

Table VI
The results of ferrographic and emission spectral analysis of the same engine on the spectrometer MOA

Type of particles	**Size**	**Missing**	**a little amount**	**a mean amount**	**a large amount**
Normal rubbing wear	<15 μm		x		
Fatigue crumbling	>20 μm		x		
Spherical particles	to 10 μm	x			
Plate particles	>15 μm	x			
Particles of hard wear	>15μm		x		
Particles of cutting wear	to 20 μm		x		
Particles of corrosion wear		x			
Particles of oxides		x			
Ferrous particles			x		
Nonferrous particles		x			
Nonmetal particles			x		
Nonmetal particles (amorphous)		x			

Conclusion on the wear of engine				
Weak	Normal	Warning	Intensive /red signal	
	Ő			

Emission spectrometer MOA , μg/g

Al	**Fe**	**Ag**	**Cu**	**Mg**	**Ti**	**Ni**	**Si**
00.0	0.2	0.0	0.1	0.0	0.0	0.0	0.0

In the table V the data of scintillation measurements are given for oils which has been collected and analyzed after ferrographic study, including washing of glass plate by the detergent. These results are given in the line "pouring oils".

On the whole, the pouring oils obtained after the ferrographic measurements have been analyzed for 12 engines. The increased number of detected particles in relation to the

source samples has been obtained. The mean size of particles in pouring oils turns to be less.

On of the explanation consists in the following.

At micro-roentgen study of the wear particles on the analyzer Camebax SX-50 the particles of resinous deposits with metal impurities were detected. On addition of the detergent these resinous particles were dissolved, resulting in the increase of a number of particles in oil sample. The fact revealed is of fundamental practical importance.

It is seen from the table V that the pouring oils contain rather large amount of particles, including ferromagnetic ones. It has been found that a number of particles in pouring oils varies random from sample to sample. This fact can lead to an essential distortion of the true values of wear parameters, and, hence, the evolving failure can be missed.
On the other hand, the results of scintillation measurements can be used as an additional diagnostics parameters, since the resinous substances with metal particles testify the quality of oil.

The table VII gives the results of scintillation measurements for the engine taken from the service.

Table VII

The results of scintillation measurements for an engine taken from the service. The work time is 703 hours

The work time is 703 hours. Oil Turbonicol	**Al**					**Ni**				
	N	**$C_d+\check{N}_p$, µg/g**	**D, conv**	**$\check{N}_{atk}$**	**$\check{N}_{aa}$**	**N**	**$C_d+\check{N}_p$, µg/g**	**D, conv**	**$\check{N}_{atk}$**	**$\check{N}_{aa}$**
	11	0.0+0.5	0.06	-	-	450	0.21+0.3	0.3	-	-
	Number of complex particles					Number of complex particles				
	AlFe 2	AlCu 1	AlAg 0	AlNi 0	AlMg 1	NiFe 449	NiCu 0	NiAg 0	NiAl 0	NiMg 0

Mg					**Ag**				
N	**$C_d+\check{N}_p$, µg/g**	**D, conv**	**$\check{N}_{atk}$**	**$\check{N}_{aa}$**	**N**	**$C_d+\check{N}_p$, µg/g**	**D, conv**	**$\check{N}_{atk}$**	**$\check{N}_{aa}$**
640	0.30+0.09	0.42	-	-	226	0.04+0.52	1.05	-	-
Number of complex particles					Number of complex particles				
MgFe 24	MgCu 23	MgAg 4	MgAl 1	MgNi 0	AgFe 9	AgCu 0	AgAl 0	AgMg 4	AgNi 0

Fe					**Cu**				
N	**$C_d+\check{N}_p$, µg/g**	**D, conv**	**$\check{N}_{atk}$**	**$\check{N}_{aa}$**	**N**	**$C_d+\check{N}_p$, µg/g**	**D, conv**	**$\check{N}_{atk}$**	**$\check{N}_{aa}$**
1640	5.3+2.7	0.25	-	-	520	0.35+0.2	2.0	-	-
Number of complex particles					Number of complex particles				
FeMg 24	FeCu 20	FeAg 9	FeNi 449	FeAl 0	CuMg 23	CuFe 20	CuAg 1	CuAl 1	CuNi 5

Unfortunately, the table does not contain data on Cr and Ti. These elements were not allowed by the used polychromator.

The comparison of the tables V and VII shows that a number of simple particles (exclusive of Al) and a number of complex ones has increased significantly. From the alloys only FeNi has been found.

From the table IV it is seen that FeNi can belong to a starter, to details of a drives body and of a separator body.

Additional indications on hardenings of latest two units are missing. Hence the hardenings FeCu and FeMg points to the fault in the starter. Besides, the increase of a number of FeAg particles testifies on the initial stage of a wear of intershaft bearing.
The taking the engine to pieces has confirmed the results made.

Conclusions: 1. The laboratory model of the scintillation spectrometer for a spectral analysis of liquids for wear products has been elaborated.

As the spectral light source the elaborated UHF plasma generator of a cyclone type was used. It is rather reliable in operation (guaranteed is 1000 hours of work), the air may be used as a base gas supplied from the compressor.

2. It enables for time 5 minutes to obtain the information on

- a metal wear particles content,
- a dissolved metal content,
- an amount of wear particles,
- an amount of simple particles,
- an amount of complex particles,
- a composition of each particle.

The procedure of spectrometer graduation on dissolved metal and metal particles has been elaborated. The metrological properties of the method have been evaluated. It was shown that the accuracy of the method complies fully with the customary requirements.

2. The emission study enables unit-to-unit diagnostics.

Results have been obtained on the laboratory model of the scintillation spectrometer. After an advancement of the registration apparatus and instructional materials an accuracy of the method may be notably enhanced.

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Effective Condition Monitoring of Aero-Engine Systems Using Automated SEM/EDX and New Diagnostic Routines

Application Appraisal:

RAF Tornado Aircraft RB199 Engine Condition Monitoring Project

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Abstract: The Royal Air Force Tornado RB199 Engine Support Authority has implemented an innovative, efficient and cost effective wear debris monitoring (WDM) programme through the successful application and adaptation of a commercial-off-the-shelf Scanning Electron Microscope/Energy Dispersive X-Ray (SEM/EDX) system. Combat aircraft engines, such as the RB199, require conditional health monitoring of oil wetted components, specifically tribo-components, for their protection against critical failure. Such monitoring maximises component life, resulting in reduced logistic and mobility footprints, while enhancing operational availability and capability. The hostile operating environments of high performance turbine engine technology (HPTET) demand hardware robustness and/or a strategic investment in an enhanced tribology capability within the maintenance arena. For post design in-service engines the latter option using state of the art technology offers by far the more affordable option, with excellent potential, at lower initial investment, for the future higher performance combat aircraft engines. The transition of electron probe microanalysis to the field combined with accurate and precise diagnostic routines based upon reliability centred maintenance and hazard risk analyses realised an immediate payback to the RAF. The RAF, in conjunction with Rolls Royce, has established the next generation of WDM techniques to support its long-term assets.

Key Words: Aero-engine Integrity; Early Failure Detection; Condition Monitoring; Wear Debris Monitoring; Oil Wetted Components; Proactive Maintenance; Electron Probe Microanalysis; Scanning Electron Microscope; Energy Dispersive X-ray Spectrometry; Total Quality Management; Continuous Improvement.

Introduction: The RAF has conducted wear debris monitoring (WDM) programmes on its aero-engines since the 1960s, when magnetic drain plug (MDP) technology called for the establishment of early failure detection centres (EFDC) at its operating bases [1]. At the outset of its service life, the RB199 engine oil system idiosyncrasies required the combination of several analytical and monitoring techniques for protection against anticipated failure modes. Later investigations revealed shortcomings in these WDM disciplines [2]. First generation condition monitoring technologies, such as magnetrometry and atomic emission spectrometric oil analysis (SOA) could not provide the required protection for the RB199 engine when analysing multi-element debris and trending conditional health.

The shortcomings of SOA, reported regularly since the University of Dayton presented an American Society of Lubrication Engineers paper in October 1985 [3], precluded its application on most RAF aero-engine oil systems. Progressive RB199 engine hardware anomalies combined with the oil system's idiosyncrasies, called for more discerning quantitative and qualitative analyses through elemental composition, with a capability of discriminating between active and benign wear. The situation called for a full characterisation of the engine oil system, its sub-systems and all oil washed components to determine the cause and effects of all generated and migratory wear debris. Several almost identical oil washed component material specifications presented a considerable analytical challenge in determining wear origins. Fortunately, advances in electron-probe microanalysis technology offered a solution through automation to realise its transition from specialist laboratory to field application.

This paper presents the successful first phase of the RAF RB199 SEM/EDX Microanalysis Project, and charts the road map for a single universal RB199 EFD discipline and support for the EJ200 engine powered European Fighter Aircraft. It provides an objective account of the SEM/EDX microanalysis system project, which lead to the system's implementation at Tornado main operating bases. The paper also addresses briefly the various shortcomings of each of the WDM techniques that deemed them unsuitable for the RB199 engine case, and also generally for combat aircraft engines.

RAF Propulsion – Early Failure Detection Policy: The RAF has a general policy, requiring the condition monitoring of all aero-engine oil wetted components. This policy is implemented through EFDCs located within propulsion shops, and during deployment; the RAF takes full advantage of technicians trained and experienced on engine type and EFD techniques. From MDP specimen analyses, EFDCs provide maintenance recommendations to the operating squadrons [4]. All early failure detection (EFD) wear debris-sampling techniques, with the exception of SOA, are truly non-destructive, enabling the retention of samples for retrospective investigation. While the RAF policy has traditionally pursued a common equipment policy, this proved to be a false economy and an ineffective insurance for some engines, notably the RB199. Each RAF aero-engine Support and Engineering Authority, (analogous in the USAF to the combination of a Special Project Office (SPO) and Air Logistic Centre (ALC) engineering), is responsible for formulating and implementing its own maintenance policy.

These policies are based upon recommendations from the engine responsible design authority (manufacturer) and RAF specialist engineering support services. Such agencies constituted an RB199 EFD project team, formed to review current RB199 WDM techniques, which then evaluated the SEM/EDX microanalysis system and its interfacing with an integrated engine database and routine fault analyser.

Tornado RB199 Engine Anomalies: The Tornado aircraft RB199 modular engine is a highly complex 3-spool system generating up to 16,000 lbf of wet thrust. RAF engines had developed difficulties with the in-service integrity of the No4 bearing failure of which, in the worst instance, could result in seizure of the High Pressure Turbine (HPT); the secondary damage being extensive and potentially threatening to the aircraft [5,6]. It is also anticipated that the engine will face escalating reliability problems through increasing exposure of installed long-life gearboxes [7]. Gearbox degradation through normal direct mechanical/tribological wear, or indirectly as a consequence of migrating oil transportable debris, demands closer and more discerning conditional health monitoring to avoid a major operational and logistic problem. Monitoring the engine oil wetted components is exacerbated by such migration and cross contamination of debris throughout the oil sub-systems. Current analytical techniques and monitoring disciplines supporting the RAF EFD policy have proved to be technically ineffective and operationally unresponsive, as well as financially wasteful in managing the logistics of the fleet and maintaining serviceability. The engine oil system's coarse filtration (80 μ) and high oil usage rate (1-2 lt/hr), dictated that any conditional health policy should be based upon the wear debris captured by each sub-system magnetic drain plug (MDP). Planned improvements to RB199 engine oil system purity will, in the future, enable MDP sampling to be supplemented by routine quantitative filter debris analysis (QFDA) using a new SEM/EDX analytical process.

Rolls-Royce RB199 Engine Condition Monitoring Initiative [8]: In parallel with the RAF RB199 engine problems, Rolls-Royce initiated a task to identify new monitoring technologies, capable of a single point replacement of the various in-service and developing field techniques. The main objectives were:

- High versatility (particle size range, capture device, analytical capability)
- Non-destructive specimen sampling
- Suitable and affordable for field application of all engine types
- High data confidence (>80%) - minimal subjectivity
- Simplistic operation and cost effective upkeep
- High degree of accuracy and repeatability
- Progressive and trainable diagnostics
- Compatibility with on-line monitors (data correction)
- Data fusion with off-line monitors (vibration analysis and performance analysis)

RAF RB199 Engine EFD Project Background: A TQM and risk management approach was lead by the RAF Aircraft Integrity Monitoring Equipment (AIME) engineering authority (EA) in Jan 96 to determine the most effective conditional health monitoring technique to secure the integrity of the RB199 engine. Active participation

by end users at EFDCs proved invaluable in determining a rational system specification for the front line to manage the engine's continued in-service integrity.

Achieving a challenging project timescale demanded a fast track, low risk, turnkey arrangement; this precluded any potential WDM option requiring R&D. The review team sponsored by the RAF's AIME EA, included the Defence Evaluation & Research Agency (DERA) Structural Materials Centre Farnborough, Rolls-Royce Materials Laboratory and the Tornado Propulsion Flight EFDC at RAF Coningsby. Potential options were evaluated in strict compliance with Chief of Defence Procurement Instructions and RAF Project Management guidelines

Wear Debris Monitoring Technology Evaluations

(1) Rotating-Disk Emission Spectrometric Oil Analysis: The RAF investigation sponsor had co-lead the 1994/95 USAF HQACC/SA-ALC-LDN combat aircraft engine trending and diagnostic (ET&D) integrated process team (IPT), which also addressed oil analysis. These investigations had been driven by several A-10 Class A TF34 engine gearbox failures. HQACC/LG reinforced the 1994 JOAP IGT [(9)] long-term objectives by endorsing the IPT's recommendation to pursue technology evaluations, with a view to replacing atomic emission SOA for combat aircraft aero-engines. While SOA can perform its intended function and achieves cost avoidance for certain components such as gearboxes, the joint SA-ALC HQACC study showed a much higher cost incurred by its discipline and process anomalies.

It is an incorrect and non-validated assumption in atomic emission SOA that all the wear particles generated by the wear process are detectable by the spectrometer. Accurate wear rate and total wear trending and modelling is almost impossible using the concentration methodology, as there is no correlation of system oil loss with loss of oil transported wear particles. There is also little or no correlation between the "abnormal wear" step function in wear metal generation and the 10-hour trend requirement, with the one exception of the onset of abnormal wear. Reducing the detectable amount of wear metals effectively increases divergence between the total wear and measured wear trend curves. SOA is largely unreliable through the nature of the arc/spark source causing incomplete burning of particles, and poor particle transport efficiency of the rotating-disk electrode ($\leq 8\mu m$ max). Furthermore, spectrometric measurement error of >1 ppm exceeds most engine wear rate limits, thereby precluding reproducible results and a meaningful 10-hour trending programme.

The SOA process, being destructive in nature, further precluded retrospective investigation and database development. The technique is considered to be past its time for high performance aero-engine WDM.

(2) Energy Dispersive X-Ray Fluorescence (EDXRF): Almost in parallel with the USAF IPT studies, the RAF had been evaluating and implementing EDXRF analysis of wear debris for RB199 engines to provide a "further analysis" capability in the field. The RAF RB199 Review Team subsequently demonstrated the ineffectiveness of EDXRF for multi-element analysis [(10)].

Standardisation across six Tornado EFDCs could not be achieved, even when presented with seeded homogeneous certified reference materials [11]. EDXRF requires homogeneous surface defect-free large fragments (>150μm), whereas the critical debris size for most high performance aero-engine bearing materials is between 5-50μm. The variation in composition of routine wear debris sampling is so wide, that regression based calibrations, upon which XRF depends, did not work; trending was impracticable.

It is currently impossible to de-convolute accurately XRF spectra acquired from of a complex, non-homogenous mix of debris particles into component alloys, as a consequence of overlapping particles, inter-element X-ray absorption, fluorescent effects and specimen topography affected the geometry of the X-ray. Also unacceptable nickel masking effects could not be eliminated through improved tuning by tungsten filters. The time taken to acquire meaningful spectra is one hundred times that taken by a SEM/EDX system, and even through optimisation it cannot reliably detect other wear materials. The technique's anomalies demanded an expensive correlation programme, similar to SOAP, to establish if fleet standardisation was possible. Ineffective operator training and poor OEM support also accelerated the breakdown in confidence in the technique. Consequently, following two validated and avoidable catastrophic failures, the RAF decommissioned its six ED-XRF units from Tornado RB199 EFDCs after only 12 months use.

(3) Fourier Transform- Infrared (FT-IR): The 1994/95 ET&D IPT pursued the JOAP TIG recommendation for technology evaluation, bringing together the TSC, HQACC, SA-ALC/LDN and OC-ALC/LPA as a TQM activity. The prime focus of attention was given to Fourier Infrared (FT-IR) Spectroscopy and Ferrographic Wear Particle Analysis by FT-IR Microscopy. The RAF discounted FT-IR Spectrometry, as unsuitable for the analysis of wear debris metallic particles, although recognising its more meaningful application in physical property testing (PPT) of oils. It was also considered to be operationally unresponsive and manpower intensive. The RAF had no requirement for the PPT of aero-engine oils or time change policies, as a consequence of high rates of oil usage. FT-IR Ferrographic Microscopy was similarly considered to be inefficient and unresponsive for self-sufficient front line application.

(4) Magnetrometry - (Debris Testing): Debris tester measurement error and poor repeatability are a consequence of the limitations of sensor head design. Investigations at RB199 engine EFDCs demonstrated the instrument's insensitivity and erratic nature for both absolute wear and wear production rate limits. In addition, the sensor cannot account for differing magnetic susceptibility; it provides only "ballpark" concentration readouts, where benign wear particles mask those of critical active wear. Little noticeable improvement was gained through supplementing it by costly "further analysis" at external scientific establishments. Indeed, the reliance upon external scientific support proved, through inappropriate timescales, to be operationally unacceptable and difficult to prioritise maintenance activities. Notwithstanding the debris tester's limited independent value as an engine health indicator, sensor head modifications enhanced sensitivity and improved repeatability, but still only offered a minimum capability in the form of an interim wear-rate "trigger".

(5) Optical Microscopy: The RAF stands out from almost all other air forces with its more objective optical analysis of MDP debris. However, it is recognised that during visual inspection, the reliability of the human brain/eye combination is relatively low, due to tiredness, limited expertise, and pressure of work or distraction. It has become an established practice throughout industry to eliminate human intervention as much as possible, relying instead on fully automated "no eyes" non-destructive inspection systems. Optical systems, either in use or under development for RB199 EFDCs, have run counter to this practice. The RAF's development of an enhanced optical microscope procedure, using a manual optical split-image and wear-debris atlas with CCTV, based ostensibly upon morphology, proved ineffective. Used in conjunction with debris testing at RB199 EFDCs, optical microscopy is slow, manpower intensive and, being dependant upon image resolution is largely subjective. The RB199 wear particle atlas (WPA) [12] project was unsuccessful as a result of not standardising the library images with in-service EFDC equipment. Improved magnification (600x) microscopes only exacerbated manual operator difficulties by constantly having to change between depths of field to accommodate the different lenses when separating out particles. A comparison between optical and scanning electron microscopy (SEM) demonstrated a daily analytical throughput of a thousand times in favour of the SEM, which also provides excellent back-scattered imaging, though this information ranks only secondary to compositional analysis in order to identify wear material type and origin. Opinion that optical microscopy provides quick and reliable analysis when faced with the aforementioned operational pressures is questionable.

(6) In summary: SOA, magnetrometry and EDXRF techniques often lead to randomly occurring cumulative errors with poor analytical reproducibility, all having demonstrated shortcomings and inconsistency in detecting incipient failure. They also require expensive correlation programmes to maintain analytical standardisation. Stand-alone or a combination of existing WDM disciplines, allowed RB199 No 4 bearing failures to continue largely undetected, while a large number of engine modules continued to be prematurely rejected through false calls. Utilisation had become reliant upon costly and imprecise logistical support, which could no longer be tolerated. Automated SEM/EDX microanalysis was the only suitable stand alone condition monitoring technique, evaluated from current and developing technologies, with a potential to achieve the maintenance management, logistic and operational targets.

RB199 Engine EFD Review Team Recommendation: Notwithstanding the high initial investment cost, acquisition of an automated SEM/EDX microanalysis was strongly recommended. A commercial-off- the-shelf universal system was justified on the grounds of expediency, in managing RB199 engine No4 bearing characteristics. Through an immediate return on investment, the planned 6-month field evaluation was compressed, enabling early minor development to interface a combined database/fault analyser with the SEM/EDX for universal operation. This early SEM/EDX success and experience also highlighted the feasibility to develop a far less expensive system. To achieve universal engine support by a single "bulls-eye" WDM discipline, development of a mobile application specific system was enabled through sustained engineering support arrangements with both Rolls-Royce and LEO Electron Microscopy Ltd, the SEM/EDX system integrator [13].

RB199 WDM Project Definition – SEM/EDX Selection Criteria

(1) General RB199 WDM Specification: The overall RB199 engine WDM specification embraced the aforementioned Rolls-Royce Engine Condition Monitoring (ECM) Initiative objectives. A self sufficient WDM system for Tornado RB199 EFDCs, capable of "hitting" incipient failure first time, every time, needed to provide:

a. Rapid and automated analysis of 100% of RB199 engine MDP samples, (16 EFH interval and reduced interval sampling). Full analysis (morphological and chemical) of 1500 individual particles, with diagnostic recommendations, such as presented on average by one engine set (5 MDPs) to be achieved within 15 minutes.

b. A fully qualitative and quantitative analysis of multi-element materials for a particle size range of 5 μm and upwards, capable of discriminating between active and benign wear generated particles. Full characterisation of individual particles, with a software capability for automatically de-linking overlapping particles.

c. A root-source wear diagnostic capability, using both absolute and trending limits by compositional analysis backed up by automated morphological analysis of constituent materials and particle details.

d. A consistent statement on the condition of the engine oil wetted components, being able to first detect and then discriminate between a range of damage and failure mode symptoms with 90% confidence.

e. A system specific compatible suite, to minimise variations in human/machine interface, with automated control to enable simultaneous analysis.

f. User friendly novice operation, with clear unambiguous procedures

g. Simple and environmentally acceptable means of sample preparation, without the need for polishing and coating, yet compatible with debris testing, optical microscopy and electron probe microanalysis.

(2) WDM Diagnostic Software: The SEM/EDX WDM diagnostic software was required to provide:

a. Historical data used to create engine specific wear data, with the ability to trend non-critical components (normal/abnormal thresholds).

b. Normal operation and different failure modes used to establish limits of wear generation for certain materials (alert/rejection criteria).

c. A capability of alerting module and component specific problems automatically based upon trend rules (fault signatures).

d. A seamless interface control between SEM/EDX analysis and engine specific fault analyser and database.

SEM/EDX Microanalysis Selection Strategy: It was readily recognised that protecting RB199 engine integrity, could only be obtained through a higher, yet "value for money", insurance premium, any risk being mitigated by using off-the-shelf proven technology. A medium financial risk was recognised in the pursuance of achieving a stand alone integrated discipline. The further analysis of MDP debris at research and scientific centres in support of the RAF and German Air Force Tornado aircraft had demonstrated undisputedly the effectiveness of SEM/EDX systems (14), albeit they were manual systems covering only just over one per cent of all MDP sampling. The feasibility study focussed on technology transition from scientific centres employing specialist operators, to a field automated system to be operated by propulsion technicians with no equipment experience. In addition to an analytical capability, the principal selection criterion was cost effectivity. The feasibility study covered a comprehensive field trial, addressing universal support from MOB through to deployed operational squadrons (15)

Automated SEM/EDX Microanalysis Project

Investment Appraisal: A comprehensive and objective cost benefit analysis was facilitated by the RAF's policy of retaining historically engine wear debris at its EFDCs. The appraisal adopted two methods. Firstly, an initial desktop investment appraisal was largely based upon SEM/EDX experience at Rolls-Royce Materials Laboratory Bristol, DERA Structural Materials Centre Farnborough and Naval Aircraft Materials Laboratory Portsmouth. From the analyses of retained RB199 wear debris, it was acknowledged that at least three recent catastrophic engine failures would have been averted, by detecting incipient or impending failure (wear) progression, representing a £750K hardware saving. Secondly, the appraisal undertook a series of analyses by a recently SEM/EDX-trained RAF propulsion technician of ten engines' wear debris to determine their conditional health, compared with existing WDM techniques. The independently validated results, showed three engines with abnormal wear (failed several hours after in-service sampling), three engines trending towards the advanced stages of wear and four "normal" engines, i.e. progressing through normal wear rate conditions. The appraisal of three independent WDM programmes also showed that cost management of each; in terms of costs per sample, favoured the stand-alone SEM/EDX microanalysis system. It also recognised a potential for reduced sampling.

SEM/EDX System Overview: The system uses sophisticated analytical routines to identify, characterise, analyse and interpret engine wear MDP and/or filter captured debris deposits. While maintaining laboratory standard and continuity, the system demonstrates enhanced usability, making it a fully practicable solution for front line (intermediate level) and overhaul and repair (R&O (depot level)) establishments. Tailoring of the standard hardware, firmware and software resulted in a system specific compatible suite based upon a SEM, that can be used to semi-automatically analyse engine wear debris and provide reliably routine diagnosis (Figure 1).

The overall control programme is initialised via a simple sequence of "windows" operations, the data generated is applied to a new diagnostic methodology and recommendations are provided based on the known rules of the subject engine system. The diagnostics are based on a versatile algorithm which processes the compositional

and morphological data gathered from each individually scanned particle, and applies it to engine specific criteria. Known engine failure characteristics established from the Failure Mode Effects Criticality Analysis (FMECA) case studies and the thresholds of general engine behaviour are used to train the software to identify normal, marginal, and abnormal wear trend and absolute conditions. The system is capable, to a high degree of confidence, in detecting wear sources and the incipient failure of oil-wetted components at an early and manageable stage [16], offering a realistic proactive maintenance policy (Figure 2).

Sample Preparation: Following their removal from installed engines, magnetic plugs are submitted in sets to the EFDC. Solvent cleaning of the plugs is first carried out to remove all organic residues. The complete contents of the plugs are then transferred directly onto an adhesive, electrically conductive medium suitable for SEM use. The debris is manually manipulated into the desired field of view (6mm x 5mm) within the central region of the tab. Particles are 'spread' using a non-metallic implement and a low powered optical microscope, to achieve a "rough particle" standard of preparation.

Notwithstanding, the manual procedure's effectiveness when considering the broad spectrum of samples presented, continuous improvement investigations into electro-magnetic preparation are already underway.

Analytical Routine: The analytical routine developed at Rolls-Royce Materials Laboratories provides a seamless process from identification through analysis and diagnostic interpretation. The process developed can be summarised as follows;

- The identification of particles via the IA thresholding of a 50x Backscattered Electron SEM image (Carbon grey level = 0, particles 70-250)
- IA processing of the field features giving individual morphological measurements such as size, shape, compactness and aspect ratio to aid in fault type identification.
- Primary and Secondary quantitative X-ray analysis to filter benign materials and classify critical alloy types (150 ms/1000 ms acquisition times)
- The sequential processing of up to 20 full chip detector or filter samples
- The import of debris derived system data into the Rolls-Royce fault diagnostic package for trending and indication of appropriate maintenance recommendation

The complete process is automatic, taking on average one hour to process four full engine samples (20 debris deposits). The EFDC operative is freed to concentrate on other duties such as sample preparation or plug cleaning.

Back-to-back benchmarking of the automated process and expert intensive manual SEM approach revealed excellent data correlation's and highlighted the huge time saving (minutes Vs hours) associated with the technique. It was concluded that the 'quality' and accuracy of the system has not in any way been jeopardised [17].

Phase I Main Operating Base (MOB) - System Performance: Six RAF Tornado MOBs are now equipped with SEM/EDX systems. The fleet leader has been in service for over one year and has processed and diagnosed over 8500 MCD samples.

Thus far, with the 100% utilisation of the system and an inspection periodicity of 16 EFHs, the RAF has not experienced a single catastrophic bearing failure on the RB199 engine. In the 12 months preceding the implementation of SEM/EDX seven catastrophic failures occurred. All modules implicated by SEM/EDX diagnosis that have been returned to third line maintenance facilities have displayed incipient bearing damage. Furthermore, regular "false pulls" of gearboxes, as a consequence of debris migration from other components, has almost been eradicated.

The operational effectiveness to-date from '**N**' arisings is summarised as follows:

Hits	100%
Misses	0 (several gearbox arisings remain unconfirmed)
Escapes	0
(Confidence	95%)

The short and longer term cost benefits of the system have been proven by:

- The elimination of nugatory engine rejections (~50% to <5% forecasted)
- The reliable detection of bearing/transmission damage (~60 hour lead-time)
- The responsive nature of the system (full diagnosis <1 hr from receipt)
- The reduction in secondary component damage (pin-point fault identification and timely rejection)
- The projected extension of time between overhaul (oil-system cleanliness)

Further maintenance cost savings are also being investigated, including the relaxation of the current MCD inspection frequencies.

RB199 Engine Wear Debris Modus Operandi

(1) Phase II – Tornado RB199 Support Bases: The much lower throughput of some five bases, but providing sufficient operational and maintenance support, warrants the scaling of a less expensive reduced functionality SEM/EDX system. These bases are important elements in the universal support of the engine. Several of these bases are semi-permanent detachments, supporting moderate to high mission tasks.

(2) Phase III – Tornado Deployment & Mobility: The ad-hoc detachment of Tornado operational squadrons, will be afforded the same standardised WDM procedure for the safe protection of RB199 engines during mobility. In pursuance of this mobility requirement, the SEM/EDX project has recognised the need for significant development and has progressed through its feasibility study to project definition, where the specification is being finalised.

Conclusion: With the use of appropriate Diagnostic routines, the application of modern electron microscopy and integrated X-ray microanalysis for routine condition monitoring has proved operationally and cost effective. System capabilities significantly outweigh current wear debris analysis technology and the transfer of laboratory based equipment into front-line maintenance establishments has been proven without consequence. The front line has recognised SEM/EDX as an essential engine condition monitoring tool, protecting RB199 engine integrity and enhancing Tornado aircraft availability, at reduced costs.

System versatility facilitates an equally effective solution to all off-line monitoring requirements, with the application of a generic system to multiple engine types the next logical step. Compatibility with future on-line technologies and fusion with other engine health parameters has already been considered, the SEM/EDX system providing an excellent means of on-line monitor calibration and fault confirmation.

The next generation of dedicated ECM tool is efficient, cost effective, compact, usable and reliable; Rolls Royce, in unison with its current and prospective customers will be pursuing its application to all other engine projects during over the coming years.

Acknowledgements:

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Figure 1

SEM/EDX - Automated Wear Debris Process Logic

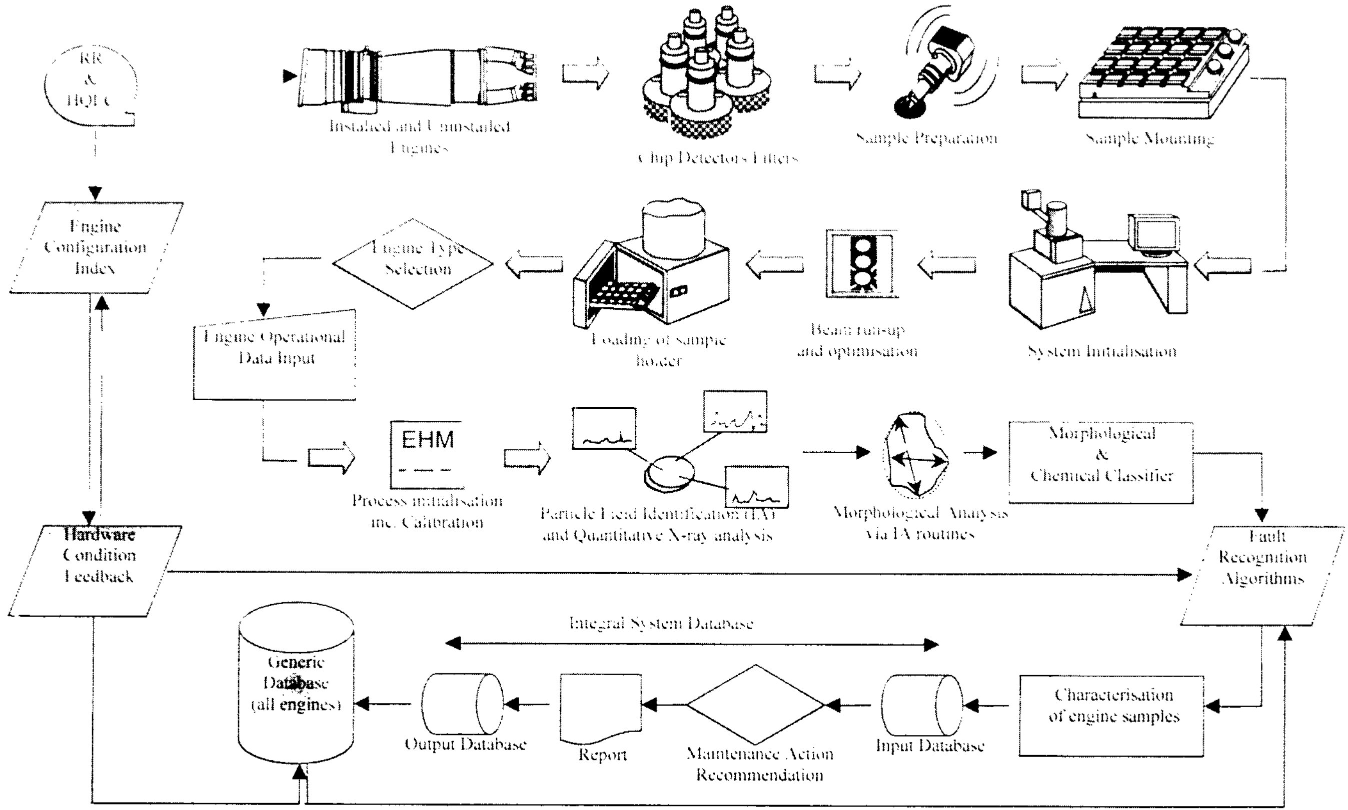
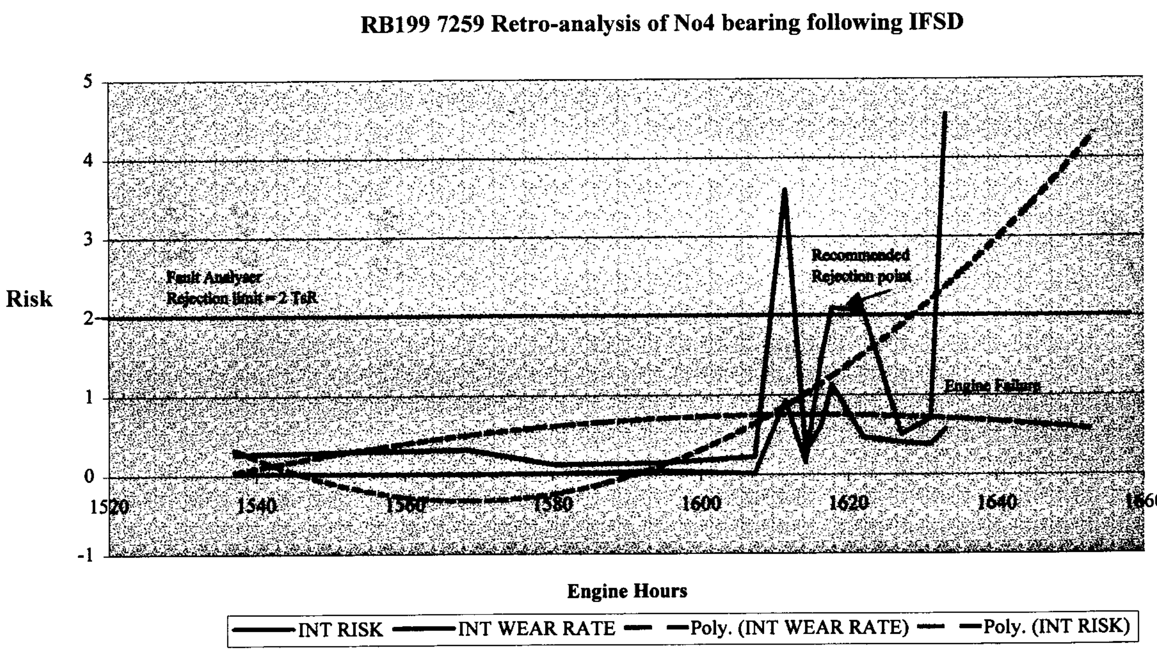


Figure 2 Rolling contact fatigue failure of the No4 Thrust bearing believed to release little or no debris prior to failure. SEM/EDX analysis using version 1 diagnostics still giving 30 hours lead-time and a clear call to reject.



Model-Based Diagnostics of Gas Turbine Engine Lubrication Systems

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Abstract: The objective of the current research was to develop improved methodology for diagnosing anomalies and maintaining oil lubrication systems for gas turbine engines. The effort focused on the development of reasoning modules that utilize the existing, inexpensive sensors and are applicable to on-line monitoring within the full-authority digital engine controller (FADEC) of the engine. The target application is the Enhanced TF-40B gas turbine engine that powers the Landing Craft Air Cushion (LCAC) platform. To accomplish the development of the requisite data fusion algorithms and automated reasoning for the diagnostic modules, Penn State ARL produced a generic Turbine Engine Lubrication System Simulator (TELSS) and Data Fusion Workbench (DFW). TELSS is a portable simulator code that calculates lubrication system parameters based upon one-dimensional fluid flow resistance network equations. Validation of the TF-40B modules was performed using engineering and limited test data. The simulation model was used to analyze operational data from the LCAC fleet. The TELSS, as an integral portion of the DFW, provides the capability to experiment with combinations of variables and feature vectors that characterize normal and abnormal operation of the engine lubrication system. The model-based diagnostics approach is applicable to all gas turbine engines and mechanical transmissions with similar pressure-fed lubrication systems.

Key Words: Model-based diagnostics; Condition-Based Maintenance; gas turbine engines; lubrication systems; simulation; data fusion; automated reasoning

Background: The primary function of a lubricant is to reduce friction through the formation of film coatings on loaded surfaces. It also transports heat from the load site and prevents corrosion. The lubricating oil in mechanical systems, however, is contaminated by the introduction of wear particles, internal and external debris, foreign fluids, and even internal component (additive) breakdown. All of these contaminants affect the ability of the fluid to accomplish it's mission of producing a lubricity (hydrodynamic, elastohydrodynamic, boundary or mixed) layer between mechanical parts with relative motion.[1,2]

Lubricant contamination can occur due to many mechanisms. Water ingestion through seals (common in marine environments) or condensation will cause significant viscosity effects and corrosion. Fuel leakage through the (turbine fuel-lube oil) heat exchanger will also adversely effect lubricity. Moreover, fuel soot, dirt and dust can increase viscosity and decrease the oil penetration into the loaded surface of the gears or bearings.[3] An often overlooked contamination, but sometimes very significant, is the addition of incorrect or old oil to the system. Table 1 provides a list of relevant faults that could occur in oil lubrication systems and some wetted components' faults.

Lubricant Faults	Gear Faults	Bearing Faults
Viscosity Breakdown	Plastic Deformation	Surface Wiping
Oxidation	Pitting	Fatigue
Emulsification	Heavy Scuffing	Fretting
Additive Depletion	Chipping and Tooth Crack	Foreign Debris
Sludge Formation	Tooth Breakage	Spalling
Fluid Contamination	Case Cracking	Inadequate Oil Film
External Debris Contam.	Surface Fatigue	Overheating
Internal Debris Contam.	Abrasive Wear	Corrosion
System Leakage	Chemical Wear	Cavitation Erosion

Table 1. Lubricant and Wetted Component Faults

Many off-line, spectroscopic and ferrographic techniques exist to analyze lubricant condition and wear metal debris.[4,5,6,7,8] These methods, while time-proven for their effectiveness at detecting many types of evolving failures, are performed at specified time intervals through off-line sampling.[9] The sampling interval is driven by the cost to perform the preventative maintenance versus the perceived degradation window over an operational time scale.[1] The use of intermittent condition assessment will miss some lubricant failures. Moreover, the employ of such off-line methods is inconvenient and increases the preventative maintenance cost and workload associated with operation of the platform.

Introduction: Maintenance actions can be performed when a component or system fails (corrective), on an event or time basis (preventative), or when an assessment of condition indicates a failure is likely (predictive). Figure 1 depicts the variation in costs with number of maintenance events. Corrective maintenance produces low maintenance cost (minimal preventative actions) but high performance costs due to the cost of operational failures. Conversely, preventative maintenance practice produces low operations costs, but more preventative actions produce greater maintenance department costs. Moreover, the application of statistical safe-life methods (still preventative) to critical systems usually leads to very conservative estimates of the probability of failure. The result of such methods is an additional hidden cost associated with disposing of components that still retain significant remaining useful life. A brief description of relevant terminology is provided below.[10]

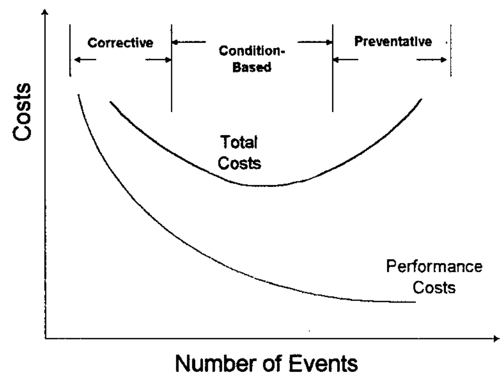


Figure 1. Cost Variation with Different Maintenance Practices (adapted from Ref. 1)

Condition-Based Maintenance: CBM is a maintenance philosophy in which equipment is maintained only when there is objective evidence of an impending failure.

Diagnosis: Identification of a particular evolving failure based on the observables sensed on a piece of equipment. Inherently, diagnosis of the state of the system must precede a prognosis or prediction of the machinery's future health.

Prognosis: The ability to provide a reliable and sufficiently accurate prediction of the remaining useful life of equipment in service. By predicting the remaining useful life, the prognostic capability assists the operator in actively managing his/her maintenance resources and recommends suitable actions.

Remaining Useful Life (RUL): Operational time from the present until a system will not be able to successfully complete its next "mission". A mission is a time when maintenance cannot be conveniently conducted. Thus, a mission separates convenient repair opportunities.

The additional CBM terms of a failure trajectory, critical prediction horizon and critical detection horizon are discussed in Reference 10. They provide elaboration on the modeling of state space evolution of a failure mode and how this relates to detection, alert and alarm structuring.

Needs and Requirements: Gas turbine (GT) engines are prime candidates for CBM for many reasons. GT engines similar to the current LCAC TF-40B, shown in Figure 2, are highly critical subsystems as power sources on numerous Navy and DoD platforms such as surface ships (for electrical power generation), tanks (M1A1), and both rotary wing (H-46, H-53, H-60, etc.) and fixed wing (F-16, F-18, etc.) aircraft. The engines operate at high temperatures and the lubricant may experience thermal degradation, oxidation, and coking, which can plug passages and damage seals. The ester-based lubricants (MIL-L-23699E) used have finite shelf lives with additives that may be quickly consumed. Oil-wetted components are the critical path for maintaining machinery alignment and transferring power through the engine and to the transmission. A significant failure in the oil will quickly lead to mechanical failure and loss of the engine. The maintenance costs for a gas turbine bearings (#1-#6) range in the tens to hundreds of thousands of dollars depending on size and precision.[11] Continuous monitoring is even more desirable with the widespread use of Full Authority Digital Engine Controllers (FADEC), which provide computer processing and memory storage to perform diagnostics in addition to the primary functions of operational mode sequencing and fuel metering.

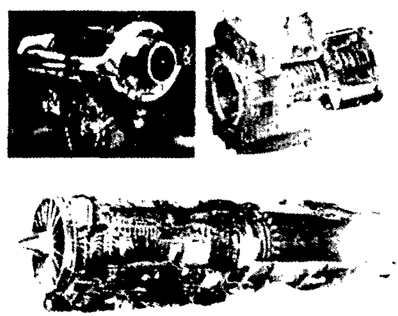


Figure 2. Helicopter, Marine and Aircraft Gas Turbine Engines (courtesy of Allison, AlliedSignal, Pratt &Whitney)

Due to the potential catastrophic effect of a failure on such high-speed machines, a great deal of usage-based maintenance is performed. Within the helicopter community such maintenance costs are about 25% of the life cycle costs. The reliability data indicates that engines are a significant portion of this maintenance cost. Typical numbers from the LCAC reliability summary, for instance, indicate the engine and propulsion related problems account for about 30%-40% of the recorded mechanical system failures. The data from the helicopter community is shown in Figure

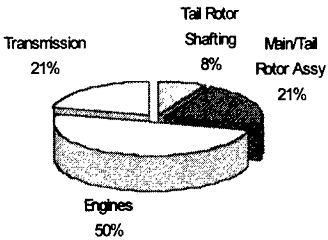


Figure 3. Mechanical System Fault Distribution (for Navy Helicopters)

3. Chamberlain[12] documents the high rate of engine-related problems and the need for Health and Usage Monitoring Systems (HUMS).

LCAC, TF-40B, and FADEC: Four TF-40B engines, which drive the lift fans and the propellers as shown in Figure 4, power The LCAC hovercraft. The LCAC transmission system includes two mechanically independent systems on both the port and starboard sides. Each combines power output from the TF40B engines on one side of the craft through right angle gearboxes and shafts running fore and aft. Power is transmitted to two in-line lift fans through the forward offset gearbox and aft to the propeller drive shaft. Manually operated disconnect clutches permit power splitting and isolation. As can be discerned from the figure, the port and starboard transmission system are mirror images of each other.[13] The LCAC is currently undergoing a Service Life Extension Program (SLEP), which includes the propulsion system, skirt design, crew station, many accessory systems, engine power capacity and control electronics.

The TF-40B, shown in the upper right corner of Figure 2, is a twin spool gas turbine with a modular design. The gas generator turbine powers the compressor and accessory gearbox. The accessory gearbox drives the main and scavenge pump. The sump is a modular unit with 7 gallon capacity. The power turbine supplies mechanical energy to drive the lift fans and propellers through clutch mechanisms.

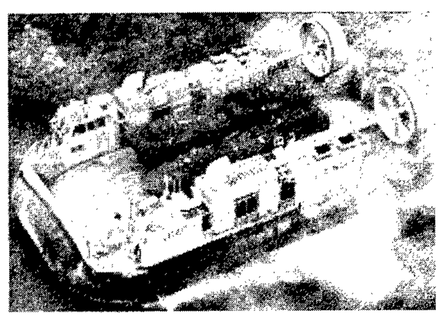


Figure 4. Landing Craft, Air Cushion

The interface to the engine sensors is through the FADEC I/O busses. The FADEC hardware includes an upgraded CPU, expanded memory, and the capability for future growth. In addition, the enhanced FADEC offers engine to engine communication through a serial network connection. The processing and memory capacities were deemed sufficient for the planned diagnostics module.

TF-40B Lubrication System: The TF-40B lubrication system is shown in Figure 5. On the left side, the main pump, which is powered through the accessory gearbox by the engine, draws flow from the sump and delivers it to the lube element. The lube element consists of a fuel/oil heat exchanger, a 7-micron filter with bypass, a "last-chance" filter in the mixing block, and a series of parallel legs to individual bearings and gears within the engine and gearbox. The flow distribution is proportioned by line friction, orifice and injection jet pressure drops. The oil filter bypass is passively caused by a high delta-p due to flow restriction (clogging). To prevent bypass during cold (high viscosity) operation, the bypass valve has a thermal lockout.

The current sensor suite is limited. The sensors that provide the most useful information from the perspective of characterizing normal mode operation and faulted conditions are the gas generator speed, the oil temperature, and the pressure to the 45 bearing. At first appearance, the chip detectors seem to provide very useful information, but much care must be taken with their use given the high nuisance rate and manual versus automatic zapping in use. In fact, some LCAC systems have automatic fuzz burning and others require the operator to discharge the detector. Correct incorporation of the chip detectors requires a significant experimental database, which was unavailable. The oil level switch in the sump and the filter delta-P switch do not provide a real measurement but rather only a switch when some limit is exceeded.

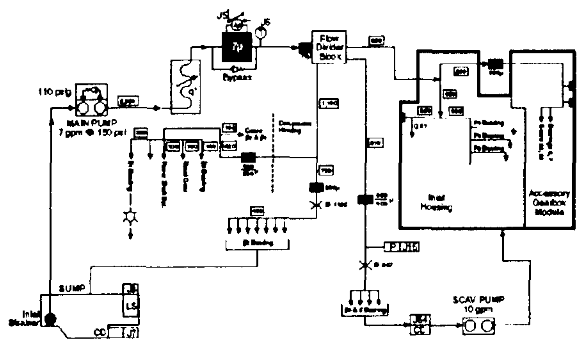


Figure 5. Schematic of Lubrication System

Procedure: The procedure on this program is shown in Figure 6. The specific components will be discussed in greater detail throughout the remainder of the paper.

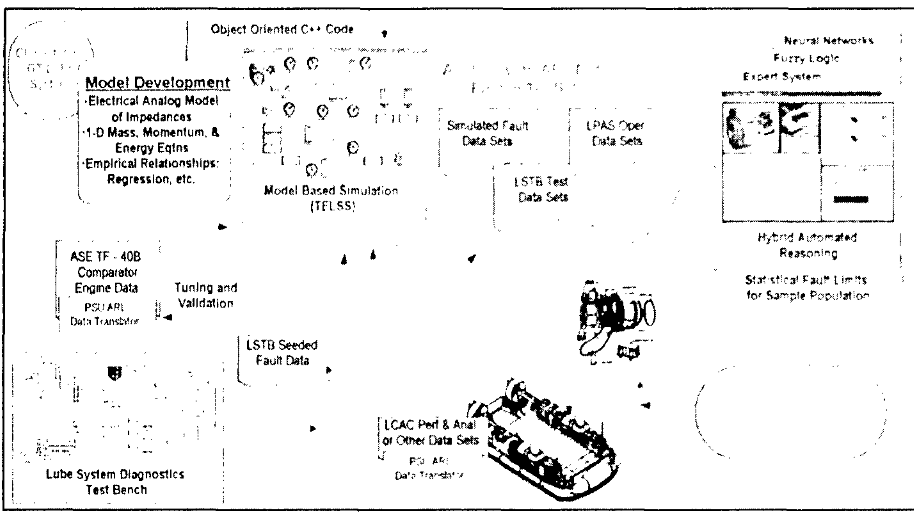


Figure 6. Evolution of Diagnostic Modules

It must be noted that association of failure modes to sensor and fused data signatures remained a hurdle in the current work. Evaluation of LPAS operational data provided some association to believed faults, but insufficient data on key parameters prevented the implementation of a fault tree or even an implicit association. A better solution would be to support this development with a lubrication systems test bench capable of evaluating failure signatures in transitional and seeded tests. This concept is further discussed in recommendations for future work. Given the lack of failure test and limited data available on the actual engine, the TELSS output was used to generate virtual sensor outputs. This data was evaluated in the data fusion and automated reasoning modules.

Turbine Engine Lubrication System Simulator (TELSS): The Turbine Engine Lubrication System Simulation (TELSS) consists of a procedural program and a display interface. The procedural program is written in C code and uses the analog of electrical impedances to model the oil flow circuit. The model contains analytical expressions of mass, momentum, and energy equations as well as empirical relationships. The interface displays state parameters using an object-oriented development environment. Both scripted and real system data can be run through the simulation. The code was optimized for on-line applications and can process a full data calculation in less than a few milliseconds on a FADEC-class processor. A great deal of effort was expended to properly characterize the Reynold's number and temperature dependent properties and characteristics in the model. TELSS requires the geometry of the network, the gas generator speed, and a bulk oil temperature to estimate the pressures and flows throughout.[14] Reference 14 provides a more thorough description of the model and parameters.

Data Fusion and Reasoning Tools: Data fusion techniques combine data from multiple sensors and information from associated databases to achieve improved accuracy and usually more specific inferences than can be achieved through a single measurement.[15] Data fusion systems are used extensively for target tracking, automated identification of targets and other automated reasoning applications. They provide the benefits of improved fault detection and a reduction of false alarms over conventional, single sensor alerts.

Significant observable synergy is possible with digital intelligence techniques such as neural networks and fuzzy logic. The use of hybrid (combined) automated reasoning appears to be an even more effective method to optimize the diagnosis of failure modes in mechanical systems. Current thesis work has indicated that a nominal weighting of 40% NN, 40 % FL, 20 % ES was effective in fatigue cracking in gearboxes.[16]

Data Analysis Results:

AlliedSignal Engines Data: AlliedSignal Engines provided data from the comparator engine test conducted in the summer of 1996. ASE performed these tests to verify the performance of a test cell that is to be used for qualification testing of Enhanced TF-40B production engines. The data generated was single design point data within the operational envelope of the engine. That is, the data acquisition system was turned on for a second or two at each steady-state condition within the test matrix. Because of this method, no continuous data streams were available. Obviously, no known faults were present in the test engine.

The data was used in several ways. The data was processed using the DFW to produce continuous data through interpolation. Typical data is seen in Figure 7. This data allowed the opportunity to trend variables against the fuel flow rate to the engine, gas generator speed and torque, and the power turbine speed and torque. Ultimately, the gas generator was deemed the most suitable regression (independent) variable for the other parameters. It was used to develop three-dimensional maps and regressions with a measured temperature to provide guidelines for normal operation.

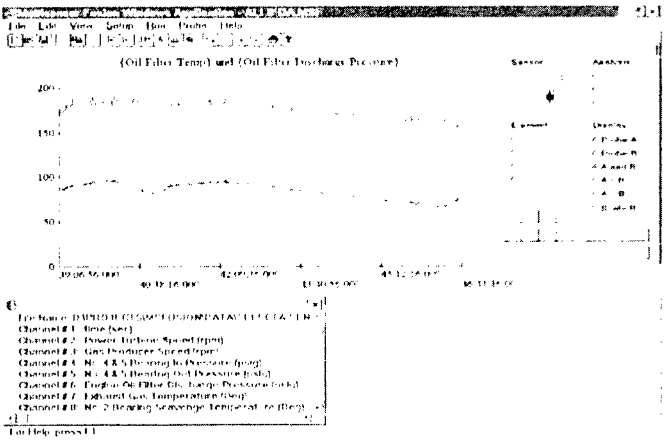


Figure 7. ASE Data in DFW

LPAS Data Sets: Operational data was made available to ARL from the Naval Coastal Systems Station, Panama City. The data was collected at NCSS as part of their LCAC Performance and Analysis System (LPAS). The data was limited to the production engine variables.

Data files were processed using TELSS in the Data Fusion Workbench. The TELSS interface for an LPAS run is shown in Figure 8. Since the condition of the oil and filter was unknown for these runs, the type of oil and a specified amount of clogging was assumed. The variation of oil and types of filters can vary the results significantly. Different MIL-L-23699E oils, which the model possesses regressions for many, may vary the flowrate predictions by 5%. Similar variation is seen when trying to apply the filter clogging to different vendors filter products. A more thorough discussion of the effects of oil properties and filter clogging is being investigated.[14]

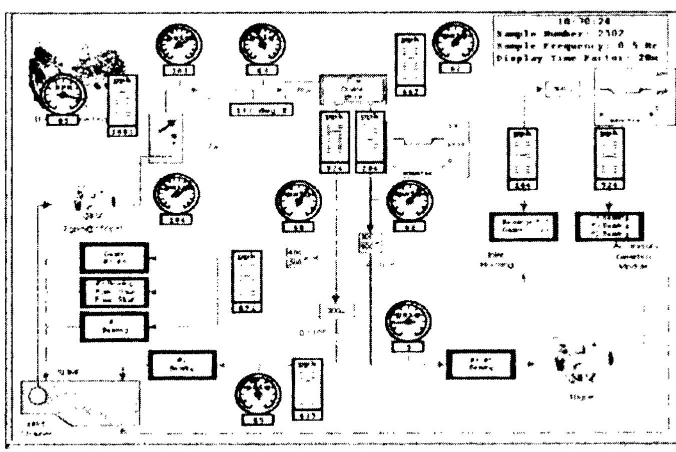
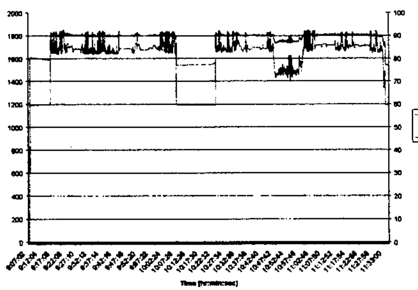
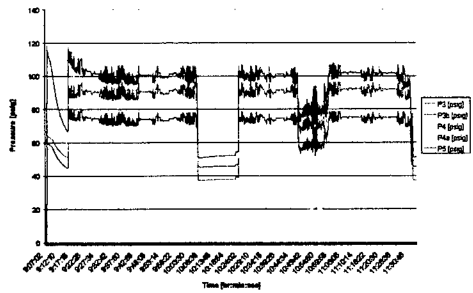


Figure 8. TELSS Processing of LCAC Run

The largest effect in predicted pressure and flow is manifested by the characterization of the pump pressure relief valve (PRV). Since the TF-40B system is designed to relieve at operating speed, its effects must be accounted for in the simulation. The pressure relief valve is treated as a variable resistance orifice that increases throughput linearly with pressure. Its flow characteristics were determined using an ASE pump qualification specification. The model predictions are good, but better characterization of the main pump PRV would certainly improve the accuracy of the simulation. Typical TELSS output graphs are shown in Figures 9 and 10.





Figures 9 and 10. TELSS Ngg Input and Mass Flow and Pressure Predictions

Discussion: The output from the TELSS/DFW was processed using an automated reasoning shell tool. The output of a shell that could be used to detect filter-clogging fractions is shown in the figures below. An expert system, a fuzzy logic association and a neural network perform the evaluations of filter clogging. The flow, temperature and differential pressure were divided into three operational ranges. The ES was provided set values for fraction clogged. The FL was modeled with trapezoidal membership functions. The NN was trained using the fuzzy logic outputs.[17] For the first case shown, the combination of 4.6 gpm, 175 deg F, and 12 psid the reasoning techniques all predict relatively low clogging. In the next case, the flow is slightly less whereas the pressure is slightly higher at 12.5 psid. The NN evaluation quickly leans towards a clogged filter, but the other techniques lag in fraction clogged. The expert system is not sensitive enough to the relationships between the variables and the significance of the pressure differential increasing while the flow decreases markedly. In this present study and others conducted at ARL, it is believed that a hybrid approach will allow the greatest flexibility in such assessments.

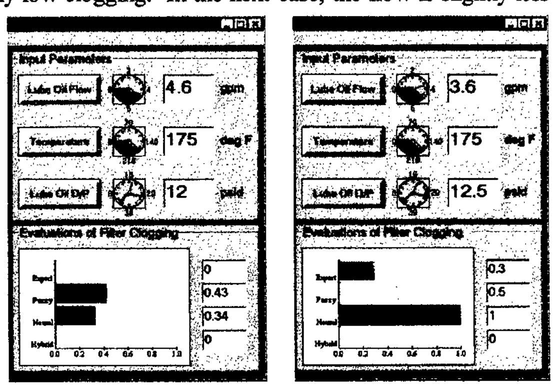


Figure 11. Hybrid Reasoning Shell Evaluation (Case 1 and 2)

The basic reasoning module for the Enhanced TF-40 B uses only the existing sensor suite to assess system condition.[14] Enhancements to the basic modules are possible with additional sensor outputs. A separate leg to the current module that logs the pressure change with varying temperature to estimate the viscosity change over a period of time could be performed by storing an array of pressure values as a function of measured temperature. An obvious enhanced module is one that includes the output of a flow and deltaP sensor at the filter as is shown in the automated reasoning shell. With these measurements, the TELSS simulation could provide direct output to the % clogged of the oil filter. Alternatively, the TELSS code could be used to predict the third variable given two of the three. At a minimum for enhanced diagnostics, a pump pressure and mass flow rate would greatly improve predictions.

Conclusion: The objective of the current research program was to demonstrate an improved method of diagnosing anomalies and maintaining oil lubrication systems for gas turbine engines. The target application was the Enhanced TF-40B gas turbine engine that powers the LCAC platform. Initial estimated data sets and ASE test stand data was used in an attempt to characterize normal operation and validate the TELSS simulation. Virtual sensors from the TELSS program and LCAC operational engine data sets were used in a hybrid reasoning shell. A simple module for the current limited sensor suite on the TF-40B was proposed and recommendations for enhanced sensor suites and modules was provided. The results and tools, while developed for the TF-40B, are applicable to all gas turbine engines and mechanical transmissions with similar pressure-fed lubrication systems.

Recommendations for Future Work: As mentioned in a previous section, the ability to associate faulted conditions with measurable parameters is tantamount for developing predictive diagnostics. A Lubrication Systems Test Bench (LSTB) has been proposed as a test platform to gather transitional and seeded data and augment this work. The LSTB will be capable of measuring system and advanced sensing data as faults and conditions requiring maintenance are introduced. Development of diagnostic models is expected to result from the fusion of the system measurements as they are correlated to an assessed damage state.

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Lastly, this work depended on the dedicated work of several individuals at ARL. I gratefully thank Derek Lang, Dave Hall, Bill Nickerson and Amulya Garga for their assistance during both the conceptual and operational stages of this development. In addition, I wish to acknowledge the efforts of Yat Shiu for writing the C code and supporting the analysis using TELSS, Karen Meister for regression analysis, and Jerry Kasmala for incorporation of TELSS into the DFW.

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A Web based FMECA Interface Linked to an Expert System for Oil Analysis

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Abstract: A World Wide Web (WWW) interface to a FMECA (Failure Mode Effects and Criticality Analysis) building tool and database is described in this paper. The WWW FMECA has been linked to an oil analysis expert system. The interface is based on an Oracle 7 distributed database tightly integrated with Web server functions. A second laboratory Oracle distributed database contains historical oil analysis data. A rule-based expert system accesses both databases and matches pertinent failure mode and detection method details from the FMECA database with current and statistical trend data from the laboratory database. The FMECA database contains both public and private data. Publicly accessible tables contain failure rates, failure mode distributions, causes, effects, detection methods, and severity classifications while private tables contain the failure mode analyses accessible only to the authenticated user. The general data tables provide cooperative and synergistic advantages to a diverse spectrum of users and industries. These advantages include consistent naming of parts and failure modes even where multiple languages are used. The FMECA database provides knowledge that is easily assimilated by an expert system.

Key Words: Condition monitoring, condition based maintenance, expert system, failure modes and effects criticality analysis, oil analysis, World Wide Web.

Introduction: FMECA, an acronym for 'Failure Mode Effects and Criticality Analysis', is a procedure for equipment reliability analysis developed by NASA and the aerospace industry and used extensively in the United States armed forces and in many large manufacturing companies. MIL-STD 1629A [1] provides a standard format for FMECA. FMECA has found use primarily in the design cycle of new products and systems because it offers a way to identify design deficiencies so that corrective modifications can be made. However, it has also been employed to a lessor extent within the maintenance planning

function [2]. Despite its many advantages FMECA is unknown among the majority of plant and maintenance engineers. Requiring training, organizational infrastructure, commitment and access to a reliable database of failure data, FMECA has not gained widespread recognition as a useful maintenance tool. This paper proposes a new approach to make FMECA more accessible to the general maintenance community.

There is a natural relationship between the principles of Condition Based Maintenance (CBM) and FMECA. FMECA includes among its procedures the identification of a *detection method* as well as the consequences or *effects* of each failure mode. Normally, in order for it to be practical, CBM must include an automated diagnostic capability. Commercial and in-house oil analysis laboratories may employ expert systems to evaluate current and trend data and to generate diagnostic reports [3]. The problem being addressed in this paper is the practical difficulty of improving the diagnostic precision of oil analysis expert systems. The solution envisioned comprises a World Wide Web based FMECA interface linked to an expert system and associated databases, schematically represented in Fig 1.

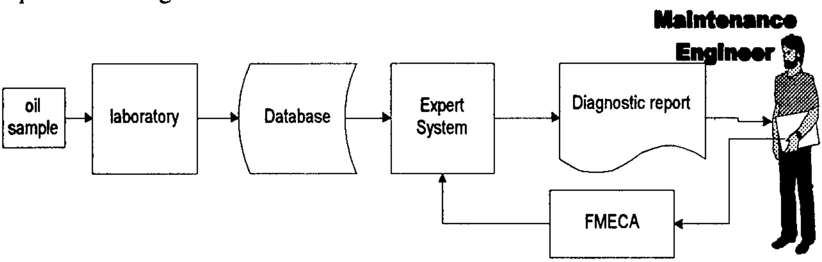

Fig. 1

Condition Based Maintenance in general, and oil analysis in particular, can be well served by the use of FMECA as their foundation. Using CBM without a preliminary analysis, one tends to collect large bodies of oil analysis data over a long period of time in the hope that trends will provide clues pointing to the failing equipment component as well as to the time remaining before the loss of that component's function. A FMECA, if performed early in the program, will guide the user in choosing an optimal set of condition monitoring techniques and relate the condition indicators to precise failure modes.

FMECA is a fundamental analysis technique that combines the analyst's intimate knowledge of each component's function, its failure modes, and the effects of each failure mode. One first collects detailed component information in a database. Useful reports are subsequently generated. Standard FMECA reports assist in the decision process regarding maintenance management policy on preventive and condition based maintenance. FMECA is the prerequisite to Reliability Centered Maintenance (RCM) [3]. At a minimum, the data compiled in the FMECA for each part are:

1. component
2. indenture level

3. failure rate, lamda
4. failure modes

For each failure mode for a component the data compiled are:

1. failure mode ratio, alpha (failure rate ratio lamda x alpha)
2. detection method
3. compensating provision
4. local effect
5. next higher level effect
6. end effect
7. severity class
8. failure effect probability, beta

A WWW FMECA program is a cost effective way to enhance an oil analysis expert system knowledge base. Ordinarily, *knowledge engineering*, that is, the acquisition of experience and its representation within a computer algorithm, is painstaking and expensive. It requires a high degree of motivation by operational personnel who must undergo interviews conducted by a *knowledge engineer*. These expenditures often have little or no immediate payback. Conversion of the gathered experience into useful knowledge in an expert system shell can be difficult where rule modifications perturb existing rules. The rule base requires periodic statistical validation against historical data.

FMECA can assist in relieving most of these problems. First, at the knowledge acquisition level, FMECA offers a tangible incentive for the user to expend time, money, and energy to provide the required domain experience. The incentive is the computer generation of useful FMECA reports, which help evaluate equipment reliability. A Web based FMECA interface allows the user to add her knowledge and experience to the rule base without without having to manipulate the algorithm within the expert system shell. The reliability reports facilitate maintenance management by demonstrating the calculated criticality of components thereby highlighting relative maintenance priorities. Since the laboratory expert system likewise publishes its reports on the Web, testing and validation are conveniently performed from within the same user interface.

The second set of problems is handled by the defined data structure exacted by the FMECA methodology. The user must, to use the FMECA software interface, be precise and systematic in specifying failure modes and effects for machinery and their components. The constrained format and strict definition of terms imposed by FMECA is, therefore, ideal for knowledge representation within an expert system.

The FMECA includes not only the failure modes and effects which occur in a system, but also the detection methods, severity classifications, and compensating provisions as illustrated by the Web input screen of **Fig. 2**.

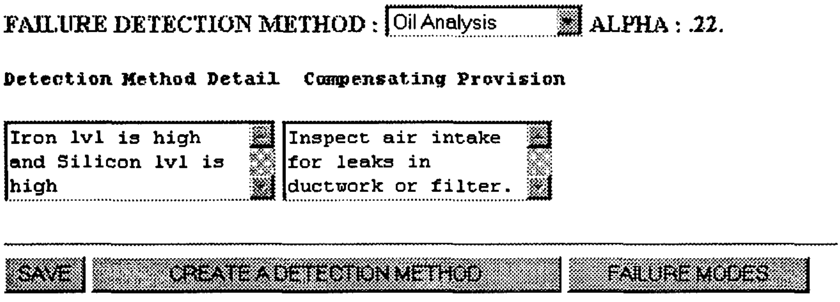

Fig. 2

The failure modes, effects, and detection methods enable the maintenance engineer to develop useful rules for inclusion into a CBM expert system. The *detection method* detail provides a triggering method for firing an expert system rule. The *compensating provision* provides the expert system recommendation. The *failure effect, severity classification,* and *failure effect probability* assign a priority within the diagnostic recommendation. The *failure mode* description and *part* description identify the likely modes of the failed component. Such vital detail, generally lacking in the reporting of many high volume automated oil analysis laboratories, is attainable through the use of an accessible Web FMECA tool as the front end to the expert system shell.

If we know, for example, that a failure mode for a system component, say a shaft, is 'misaligned' and it's *next higher level effect* is 'excessive noise' on the gearbox, an oil analysis *detection method* may state that the iron rate of increase is greater than .05 ppm/hr. The expert system rule could suggest the failure mode - namely shaft misalignment - is occurring and also suggest a confirming test for bearing noise or heat as described by the *next higher level effect.* Moreover, a statement of relative importance will have been included in the diagnostic report since the expert system will have accessed the *severity classification* and *failure effect probability* within the relevant FMECA database record.

The integration mechanism between the FMECA database and the expert system employs a database trigger to generate an appropriately formatted rule. This rule is appended to a file whenever a *detection method detail* record has been updated or inserted into the database table. The appended rule applies exclusively to the machine in question. Since the expert system shell requires that the rule be compiled, a timed UNIX command (cron) detects the modified rule file and executes the rule compiler. In this manner the expert

system becomes dynamic. That is, it is continuously 'improved' on-the-fly as FMECA data is updated by remote users. Otherwise stated, the FMECA interface empowers maintenance personnel to apply their specialized knowledge directly to the expert system rule base.

A number of benefits of the FMECA interface on the Web have been postulated:

1. Users gain a cost/benefit advantage because high-end hardware and software are justified where a single server serves multiple clients. (This would not be the case were these assets limited to single client use.)

2. The phrases describing machine types, components and failure modes are standardized. This standardization is effected through a feature of the software that encourages the user to search for an existing phrase that may spare her the task of creating a new one. By having everyone sing from the same sheet, rule maintenance and consistency are improved.

3. Given that FMECA is an already established and proven methodology, the proposed Web based interface to FMECA should expand the number of maintenance users who can benefit from it.

4. When an oil analysis report appears to be inadequate in predicting failure or establishing machine health, a FMECA is launched directly from the Web published report.

5. Since the general FMECA database tables are used and developed by multiple users from diverse industries, there is a synergy based on cooperative development and acceptance of FMECA phrases.

6. The software is always up-to-date. The Web FMECA user interface is an example of *thin client technology* that requires a minimal hardware configuration. Users need only a Web browser to access the software's full functionality. It is not necessary to maintain the software or the data on the client computer. Administration, backups, and upgrades are the responsibility of the server.

7. Failure rate and failure mode databases are maintained an updated for the user.

In a nutshell, a World Wide Web FMECA interface, provides the maintenance manager with the ability to understand the failure modes and their effects on the costs of maintaining her plant. This information appears in a variety of reports which highlight the failure modes and rank their criticality levels. These reports become the basis for important cost saving management decisions. At the same time, precise diagnostics are possible in CBM expert system-generated reports whenever a monitored parameter coincides with a *detection method detail* previously entered into the FMECA via the Web application.

The current version of the FMECA Web interface described in this paper consists of:

1. A rudimentary FMECA Web program accessed via a Web browser.

2. An Oracle database populated with suggested reliability failure mode data, FMD-97 [4], and failure rate data, NPRD-95 [5] accessed under license from the Reliability Analysis Center.

3. A help function linking to a FAQ (Frequently Asked Questions) hypertext document including FMECA examples.

5. An on-line tutorial which walks the novice through various sample FMECA examples.

6. Basic FMECA reports and user customizable reports.

Conclusions and future work: The Web FMECA interface is a promising new avenue towards the integration and unification of CBM techniques (other than oil analysis) into a common expert system. These include vibration analysis, thermography, and performance parameter monitoring which are considered additional detection methods in the FMECA database. The Web interface could be expanded to permit upload of data from these other condition monitoring sources.

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Harnessing Internet and Intranet Technology for Oil Analysis

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Abstract: The incorporation of Internet/Intranet technology into used oil analysis laboratories provides cost-effective, powerful solutions for operational needs and customer requirements. An Internet-based application also has reduced requirements for development, deployment, and maintenance when compared to client-server systems. Also, Internet/Intranet technology can coexist with existing client-server systems, providing to the laboratory enhanced and expanded functionality to support changing requirements. Laboratories can realize the power of Internet/Intranet technology in two major areas. First, Internet-based laboratory applications provide a dynamic mechanism for information distribution to customers. Delivery of analysis reports by fax, mail, and BBS is replaced by e-mail delivery and on-demand information access by customers. Since many oil analysis customers are very mobile, remote access to their information via Internet technologies such as e-mail and laboratory websites offers a significant benefit to the customer. Second, with an Internet-based application accessed via the Internet or a corporate Intranet (a private model of the Internet), samples can be received and tested at any number of remote sites with the information transferred to the central laboratory database via the Internet-based application. The central location can access the same central laboratory database and develop sample analysis and evaluation reports for distribution to customers.

Key Words: Client-server; Internet; Internet-based application; Intranet; laboratory database; oil analysis; on-demand access; remote access.

Introduction: In discussing the benefits of implementing Internet technology to improve laboratory operations, we must first define the technology components of which we speak. We will assume at this point that the reader has at least a minimal understanding of what the Internet is. The components which we see as being used in an Internet-based application include World-Wide Web pages (screens), e-mail (electronic mail), and FTP (file-transfer protocol). These components represent ways for users to retrieve information from or deliver information to an Internet server. In order to offer these services to users who connect to an Internet server, the server must have special programs

running. To deliver information via web pages or FTP, the server must run software like Microsoft Internet Information Server. This software equips the server to deliver and receive files via FTP, display web pages to users, and receive web page input from users. Software such as Microsoft Exchange Server allows the server to receive and deliver e-mail messages.

For the client end of these transactions, the user needs only two software components. The first component is a 'web browser'. A web browser is a program which is designed to receive pages from an Internet server and display them. In addition, this program allows the user to input information into a web page and send the information back to the server. The most recognized examples of a web browser are Microsoft Internet Explorer and Netscape Navigator. In addition to displaying web pages, the web browser can also facilitate file download from a server or upload to a server via FTP. The second software component is an e-mail program. This program allows the user to receive e-mail messages and send e-mail messages, and even both with files attached. The installation of a web browser and an e-mail program are the extent of components required on the client (user's) machine.

An Internet-based application is more than just a website. Websites are predominantly designed to deliver information to users with very little input back to the server. In contrast, an Internet-based application is designed for accommodating interaction between the user and the server to accomplish tasks such as entering sample test results. We have previously discussed two software components on the Internet server. In order to interface with laboratory data, a database server component is required. This component will provide laboratory data in the web pages requested by the user as well as receive and store input from the user. An example of a database server component would be Microsoft SQL Server or Oracle. The Internet-based application communicates to the database server component via an ODBC (Open Database Connectivity) connection. By using an ODBC connection, the Internet-based application can interact with any database server which is ODBC-compliant.

While we continue in this discussion to refer to an Internet server, this does not mean that the server is connected to the Internet. It means that the server functions like the Internet server model. A server can be connected to a corporate local area or wide area network and not be accessible by anyone not connected to the corporate network. This picture of an Internet server and client workstations connected to a network is the definition of a corporate Intranet. It functions identical to the Internet model, yet users not connected to the corporate network cannot access the server's information.

In the following sections, we will discuss two areas where these technology components we have identified can be implemented to serve the needs of an oil analysis laboratory.

Serving The Laboratory: In order to address how Internet/Intranet technology can support the needs of an oil analysis laboratory, we must first identify the major processes.

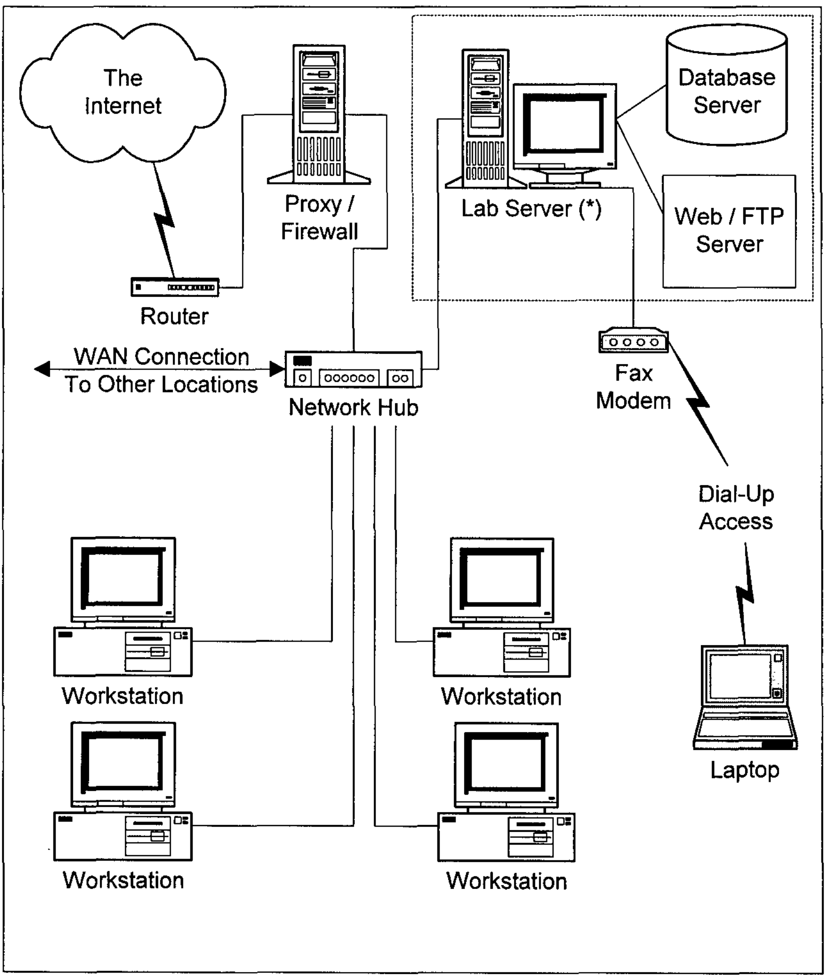
1. Sample Receiving & Logging
2. Sample Testing
3. Sample Test Data Entry
4. Sample Data Evaluation
5. Analysis Report Development
6. Report Distribution

While not directly part of the workflow described, Administration of users and reference information is also a necessary component of laboratory operations. Processes for interaction with accounting or other business systems are not listed here, but this does not mean that Internet/Intranet technology can be beneficial in these other areas as well.

An Internet-based application can be implemented in one of several ways. If there is no existing Laboratory Information Management System (LIMS) in place, an Internet-based application can perform all of the necessary LIMS functionality. This application would encompass the needs of the processes listed above as one cohesive application. In those cases where a LIMS exists, an Internet-based application can coexist with the LIMS, providing expanded and enhanced functionality while interacting with the LIMS database. An Internet-based application is a framework of individual pages (or screens) which are connected together by logic and hyperlinks to other pages. A hyperlink is a listing of another page's name or topic which, when selected by the user, moves the user to the selected page. Each page of an Internet application is a self-contained unit; it can be managed and updated as an individual file. For this reason, keeping the application up to date with the changing needs is much easier than with traditional client-server applications. In traditional client-server applications, the application must be taken off-line, modified, compiled, and the installation on each client updated. During this time, the application is unavailable to all users. With an Internet application, a new version of single page can be prepared and deployed while users continue to run the application. Once the page has been revised and deployed, the next user to access that page gets the revised functionality immediately without any client software updates required. This granularity of the application allows the laboratory to make and deploy modifications quickly without interrupting current activities.

A traditional multi-user client-server application for a laboratory interacts with a laboratory database to store and retrieve information. A database server access license is required for each client (user) running the application. The cost for a large quantity of database licenses can be significant. Further, each workstation added must have the software installed for the application. With an Internet-based application, the number of concurrent users is solely limited by the server capacity. The Internet-based application interacts with the laboratory database as an intermediary, requiring only one database license regardless of the number of concurrent users. This means that adding more users to an Internet-based application requires only the workstation hardware along with a web browser. The Internet-based application resides on the server.

Internet-based applications are fully capable of receiving bar coded information as user input for sample receiving and sample identification. The application is capable of full interaction with the laboratory database via the pages presented to the user. In an Internet-based application, it is possible to develop spreadsheets with intrinsic formulae and calculations as needed for test data entry and data validation. Spreadsheets can also be developed for data analysis and evaluation. The spreadsheet format can also be used for analysis reporting with intrinsic graphs and charts based on the reported data. These user-defined spreadsheets can be easily integrated into the application user interface.



With an Internet server, analysis reports can be distributed in the traditional ways of printed reports delivered by mail and by manually-initiated fax. Beyond this, an Internet-based application can automate the process of report distribution. Reports can be automatically delivered to printers and fax machines. In addition, report information can be automatically delivered as e-mail messages or as files attached to e-mail messages. Reports can also be delivered to an FTP site on the Internet server; the customer can then download the reports at their convenience.

Because the application is designed as an Internet application, it is inherently multi-user. Because the application resides on an Internet server connected to the corporate network, it is available to all users who are connected to the corporate network. A corporate wide-area network specifically connects together multiple geographic locations of a company. The Internet application is accessible to all locations of the wide area network. Dial-up access can be established to the Internet server and the Internet server can be connected to the Internet through a dedicated Internet connection. What does all this mean? It means that a laboratory operation can be comprised of multiple geographic locations connected together as one laboratory enterprise. Samples can be received, logged and tested at various remote locations with either wide-area network, dial-up or Internet connection to the application. The data is entered into the application and is available to analysts in a central location where the laboratory database is located. The evaluation is performed and the results are automatically delivered by fax, e-mail or ftp.

What is required to implement an Internet-based application? The diagram on the previous page illustrates the requirements. In order to implement a multi-user Internet-based application, the first requirement is a network infrastructure. This is the wiring which connects all of the workstations and servers to a hub or set of hubs. This is commonly referred to as a network. If the network is a LAN (local area network), then only computers in a single geographic location are connected together. If the network is a WAN (wide-area network), then there is a connection from the hub in one location to a hub in another location. In either case, all the computers connected to the network are viewed as one enterprise. The second requirement is the implementation of a server or servers for the laboratory. The two components on the server(s) are a database server program and an Internet server program (for web/ftp). These components can be implemented on the same server or on separate servers as desired. If there is an existing e-mail system, the Internet server requires an account on the e-mail system in order to be able to deliver information automatically by e-mail. If there is no existing e-mail system, the Internet server will need an E-mail server program such as Microsoft Exchange Server. Workstations require only web browser software; e-mail software is optional.

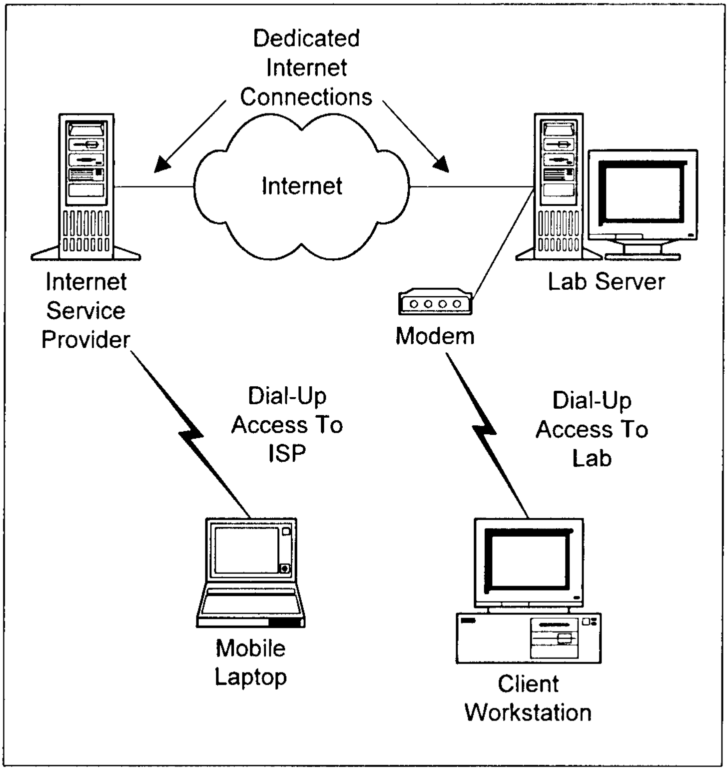
In order to support server access by remote (to the network) users, there are two options. A modem connected to the Internet server can provide dial-up access to the Internet-based application through Remote Access Services. The second option is to establish a dedicated Internet connection. This option requires a dedicated connection to an Internet Service Provider (ISP), typically by ISDN phone line or leased line. This line is connected to a router, which is in turn connected to a proxy or firewall server. The proxy/firewall server provides controlled access via the Internet to protect the overall

system from unwanted intrusion. The output of the proxy/firewall server is connected to the existing network hub. This completes the circuit from remote users to the Internet server for access to the application. For remote users, it is acceptable to support both Internet and Dial-Up access.

What are the benefits of implementing an Internet-based application? The application is constructed in such a way that the number of users has no significant impact on performance and increasing the number of concurrent users has no cost impact on database server licensing. Adding additional workstations requires only an operating system and a web browser; no other software installation is required. The application has the granularity of each individual page. Pages can be updated or modified with industry-standard tools and deployed without taking the system off-line. New pages can easily be added without negatively impacting existing pages or systems. The required skill level of those who would modify or maintain the application is significantly lower than any other client-server system approach. The application can be developed to extend existing laboratory processing capabilities without impacting existing systems. The laboratory can work as one enterprise even though users are not necessarily located in one geographic location. Remote users all over the world can work effectively as part of the same enterprise.

Serving The Customer: This is an area where an Internet-based application provides tremendous potential benefits. The customer has a number of needs associated with laboratory information. One need is the ability to track samples that have been sent for analysis. They need to know if and when the sample has been received and if the analysis information is available. The customer needs to be able to receive results regardless of their current geographic location, mobile or stationary. The laboratory does not need to spend any time or effort is making the customer's information accessible. Laboratories are not in the business of developing, distributing, and supporting software for customer access to results. Any time spent on this is counterproductive to laboratory profitability and throughput. In this vein, it is important to offer a solution which eliminates any special remote access software from being used by the customer. At the same time, the customer needs the ability to generate hard-copy reports on-demand. The customer needs to be able to have more input into the processing of his samples. In some cases, this means making requests for additional tests or different reporting formats. The customer needs to have the ability to change the priority of individual samples sent for analysis. The customer needs to be able to identify in advance that a sample requires special handling or turnaround time prior to the sample being received by the laboratory.

An Internet-based application has the potential to address each and every one of these needs and more. The application for the laboratory can have specific pages designed for customer access. These pages would control where in the application the customer can go and what they can access. Essentially, the customer could become a remote member to the laboratory enterprise. The customer could connect to the application either through the Internet or through dial-up access to the Internet server. The diagram on the following page illustrates the possible connection paths.



If the customer is only going to receive laboratory information via e-mail, then the customer only has to connect to their Internet Service Provider and poll for e-mail messages. If the customer requires more direct access to the laboratory information, they would connect as a remote user as indicated in the diagram and login to the laboratory system. Once the customer has connected as a remote user and logged in to the laboratory application, the application has full control of the access and information provided to the customer. At this point, the customer can begin to act as an integral part of managing sample information. The customer can fill out requests for sample processing or order sample kits on-line. In filling out requests for samples, the customer can perform data entry on some items that now are being filled out by hand by the customer and manually transcribed by sample receiving personnel.

Because customers could connect to the 'live' system, information to which they are granted access is always current; there is no delay between posting of analysis information and the customer being able to retrieve or review the results. Because of the granular design of the application, customer requests for changes and additional access can be quickly and easily handled. Allowing customers to connect to the laboratory application would require no additional licenses or database connections. Customers

could have on-line access to their results and reference information for research purposes. Customers would be able to download their results on-demand. If a customer agrees to retrieve information on-demand or receive information automatically via e-mail, the resources for printing or faxing are eliminated completely. By working directly with the customer, the laboratory can have advance information on samples to be analyzed and the customer can have access to the results as soon as they are posted. Customers would have access to tracking samples to know when they are received and when they are analyzed.

Summary: With Internet technology and an Internet-based application, the laboratory could support multiple locations anywhere in the world as one enterprise. Similarly, customers could access their information from anywhere in the world. The boundaries of geography can be effectively eliminated for customers as well. Sample turnaround and results reporting time can be reduced to the bare minimum. Responsiveness to customer requirements and changing operational needs can also be improved. The implementation of Internet/Intranet technology can provide significant enhancements to the laboratory operation and customer relations. The costs of implementing the necessary infrastructure is minimal when there is an existing network. The value of providing connectivity to the Internet is small in comparison to the capabilities offered by such connectivity. Laboratories can grow beyond their physical boundaries and develop partnerships with other facilities to provide a greater scope of customer coverage. Internet technology will provide the means for laboratories to enhance the systems they have and expand their horizons to accommodate the needs and wishes of tomorrow.

Using Expert Systems for Fault Detection and Diagnosis in Industrial Applications

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Abstract: This paper intended to motivate the introduction of the expert systems within the supervisory systems used in the automatic control of the industrial processes. Some concepts related to the problem of supervision and diagnosis, as well as the functions and principles associated are briefly presented. Emphases is given to the use of expert systems for diagnostic purposes. Some results obtained by the author in implementing an expert shell and using it in building real time expert systems for performance analysis and diagnosis are presented. The contribution shows how the fault detection and accommodation can be achieved through a proper integration of in process on-line monitoring and diagnosis expert system.

Key Words: Diagnosis, expert system, graphical user interface, performance analysis, real time.

Introduction: An expert system shell can be used as a base for the implementation of a real-time expert system for performance analysis and diagnosis of an industrial process. It assures a mechanism able to simplify the operator's job of recognition of the emergency state, diagnosis of the fault and initialization of the necessary corrective actions, offering him the alarms list and messages to define the primary cause as well as a list of priorities of potential solutions [1].

The use of such a system has the following results: prevent key components damages, extend critical components life-time, improve overall system performance and reliability, minimize off-line analysis efforts and maintenance costs, assist the maintenance activities, generating functional reports, and allow remote plant diagnosis and evaluation.

Basic Concepts of Fault Diagnosis: Due to the increasing complexity and risking of modern control systems and the growing demands for quality, cost efficiency, availability, reliability and safety, the call for fault tolerant in automatic control systems is gaining more and more importance [4].

Within the automatic control of technical systems, supervisory functions serve to indicate undesired or non-permitted process states, and to take appropriate actions in order to maintain the operation and to avoid damages or accidents. The necessity of such functions is required by the increasing complexity and risking of the modern complex

systems and the growing demands for quality, economy, availability, reliability and safety. Consequently, the growing demand for fault tolerance is to be achieved by both improvement of the reliability of the functional units and efficient fault detection, isolation and accommodation [3].

In this context, a *fault* is understood a any kind of permanent modification of the physical characteristics of a system or of one of its components that causes a malfunction in the actual dynamic system, the plant, that leads to an unacceptable anomaly (a failure) in the overall system performance. Typical examples for such faults are: defect constructions, faults in the drives, faults in sensors, abnormal variations of the parameters, and external obstacles [5].

An automatic control system consists of actuators, the plant dynamics (components), and the sensors. From the faults point of view, it is useful to divide the faults into three categories: actuator faults, component faults and sensor faults. The faults are described as inputs. In addition there is always modeling uncertainty due to unmodeled disturbances, noise and model mismatch. This is taken into consideration as vectors of unknown inputs.

The following supervisory functions can be distinguished [8]:

a) *monitoring*: measurable variables are checked with regard to tolerances and alarms are generated for the operator;
b) *automatic protection*: in the case of dangerous process state, the monitoring function initiates automatically an appropriate counteraction;
c) *supervision with faults diagnosis*: based on measured variables features are calculated, symptoms are generated via change detection, a fault diagnosis is performed and decisions are made for counteractions.

The classical methods (a) and (b) are suitable for the overall supervision of the processes. Their big advantages are their simplicity and reliability. Advanced methods of supervision and diagnosis (c) are used as an active approach in order to achieve fault tolerance and to provide fault accommodation, i.e. a reconfiguration of the system when a fault has occurred. To this end, a number of tasks have to be performed [9]: early detection of small faults with abrupt or incipient time behavior, diagnosis of faults in the actuators, process components or sensors, detection of faults in closed loops, and supervision of process in transient states.

The basic tasks of fault diagnosis are to detect and isolate occurring faults and to provide information about their size and source [5]. This has to be done on-line in the face of the existing unknown inputs and without or with only very few false alarms. As a result, the overall concept of fault diagnosis consists of the three subtasks: *fault detection, fault isolation and fault diagnosis*.

Hierarchical structures are now currently used in automatic systems. The following main functions have to be performed: data acquisition from the system via sensors, process

control, process supervision in order to provide control enforcement via fault accommodation capabilities, and process management.

Fault Detection Methods: There are three types of methods which can be applied for fault diagnosis:

1. The *signal- based methods* are well established in practice. In this case, the maximum advisable information concerning the faults, which could appear in the system, is carried by directly measured signals or by the corresponding symptoms extracted from the system. These symptoms are directly used for fault detection and localization or after the data processing is performed. Such typical symptoms are: time variable magnitudes of the measured signals, maximum or average values, limit values, statistical moments of amplitude distribution, spectral power densities or frequencies, correlation coefficients, covariances, etc. The efficiency of the signal-based methods is limited, these methods being used for the early detection of the faults which can appear in the dynamic of the systems under consideration.

2. The majority of fault detection approaches uses knowledge about the physical processes in the form of mathematical models (*fault detection based on analytical models*). This approach is more efficient than the signal-based one. In this case, the actual behavior of the system is compared with that of a normal fault-free model driven by the same inputs. The dynamic behavior of the system is described using the relationship between the measurable quantities in the form of a quantitative (analytical) model. If available, a perfect analytical model describes the most detailed and concise knowledge about the process.

3. However, it is very difficult to obtain accurate process analytical models, being practically impossible in the case of complex systems. The *knowledge- based methods* represents a complementary solution for the analytical methods used for fault detection. They provide a new dimension of the fault diagnosis of the complex processes, where the knowledge is generally incomplete. In this case, the system behavior is specified using both heuristic symptoms and qualitative descriptions in the form of rules and facts, obtained from empirical human observation.

The combination of these strategies allows the evaluation of all available information and knowledge of the system of fault detection.

Motivations for the Use of Expert Systems in Process Supervision and Diagnosis: The traditional methods - (1) and (2) - are well established and provide a rapid development, but are limited in their efficiency. The role of the knowledge-based approach in process supervision and diagnosis is to provide some interesting solutions for the supervision problems. It is necessary to consider this approach not as a substitution of the traditional methods, but as a supplementary tool for an engineer who has to find a solution to a specific problem. The role of the knowledge-based approach for fault diagnosis can be considered from several points of view [6]:

- *declarative*: the implementation of several reasoning strategies (prediction, postdiction, diagnosis, etc.) is permitted and is not based on the existing knowledge;
- *explicative*: the man-machine co-operation is enhanced, using causal reasoning as a base for diagnosis and explanations;
- *management of different types of data*: imprecise (measurement noise), incomplete (sensor faults), non-homogenous (logical and analogical data), dependent of the context, temporal, etc. These data are used in order to include in the system all the available information, even the heuristic one.

In the knowledge-based techniques, any symptoms can be used instead of output signals and the robustness can be attained by restricting to only those symptoms that are not or not strongly dependent upon the system uncertainty. This technique can be applied in all three phases of fault diagnosis, the theory of diagnosis being developed from first principles (system structure and behavior descriptions).

The residual evaluation is a complex logical process which demands intelligent decision making techniques like fault trees. Therefore, knowledge-based methods are a quite natural approach in fault diagnosis and the *expert systems (ES)* are applied more successfully in this field that in the control domain. This was the result of an analyze of about 2500 expert system (Durkin, 1994). Figure 1 proves that the diagnose is a field in which the ES role is predominant because ES plays the same role as an human expert and are easy to develop, the number of possible solutions and information being finite.

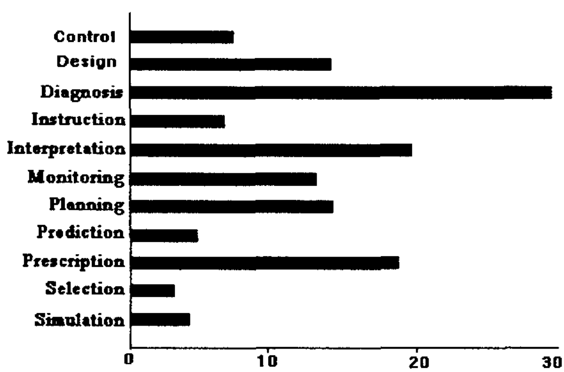

Fig. 2 - % Applications (Durkin, 1994)

The Architecture Of Fault Detection And Diagnosis System: The architecture of the fault detection and diagnosis system is presented in Fig. 2. The core is an on-line expert system which complements the analytical model-based method with the knowledge-based methods using heuristic reasoning. The resulting overall fault detection system consists of the following architectural components:

- *knowledge-base* with heuristic (qualitative) process models expressed in form of rules related to the physical cause-effect relationships;
- *data-base* with information (facts) about the present state and the history of the process;
- *inference engine* which combines heuristic reasoning with algorithmic operations in terms of evaluation of the analytical redundancy;
- *explanation component* used to inform the user on why and how the conclusions were drawn;
- *co-ordinating routines* which assures reliable communication with the monitoring application, internal synchronization and data-base and knowledge-base consistencies;
- *user interface* which is a windowing type interface used for both building and exploitation of the system. Some major characteristics are: representation of the structure of the system; automatic alarming of the operator, on-line displaying of data and messages, high speed in providing the system reaction to fault conditions.

The knowledge of the system is acquired from an expert who might be not the same person as the user.

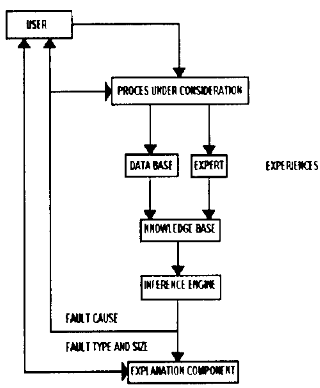

Fig.2 - Architecture of the fault detection and diagnosis system

Expert Systems for Performance Analysis and Diagnosis in PV Plants: The paper aims to present the results obtained in the implementation of an expert shell that can be used to develop a real-time expert systems. This expert shell was used as a base for the implementation of a real-time expert system for performance analysis and diagnosis of a PV plant, in the frame of a Joule II European project. The results obtained using this expert system in Zambelli PV plant (near Verona, Italy) are also presented in the paper.

A photovoltaic system can be represented by a transfer function with the solar irradiance as input and an electrical value (power, etc.) as output [7]. The components of a *PV plant* are PV array (made by monocrystaline or polycrystalline cells), batteries (usually Pb

batteries) and power conditioning block (converters, rectifiers, switches and inverters). The PV pilot plant Zambelli is a part of the water pumping station for Verona city and consists of PV arrays of 70 kW and 360V, two inverters of 35 kWA with variable frequency, two strings of batteries of 300 Ah.

In global supervision of a PV plant, an important amount of data is measured and calculated by the monitoring system in order to analyze the system performances and to detect and diagnose the possible faults. These data are inhomogeneous (logical and analogical data), temporal, imprecise (affected by measurement noise) and incomplete (due to sensors' faults). There are hundreds data linked by complex relationships. Heuristic and qualitative observation (i. e. for meteorological conditions) have to be used. That is why the utility and validity of analytical models is quite uncertain, especially in case of faults. The expert systems provide new interesting solutions for supervision problems, and taking of intelligent decisions.

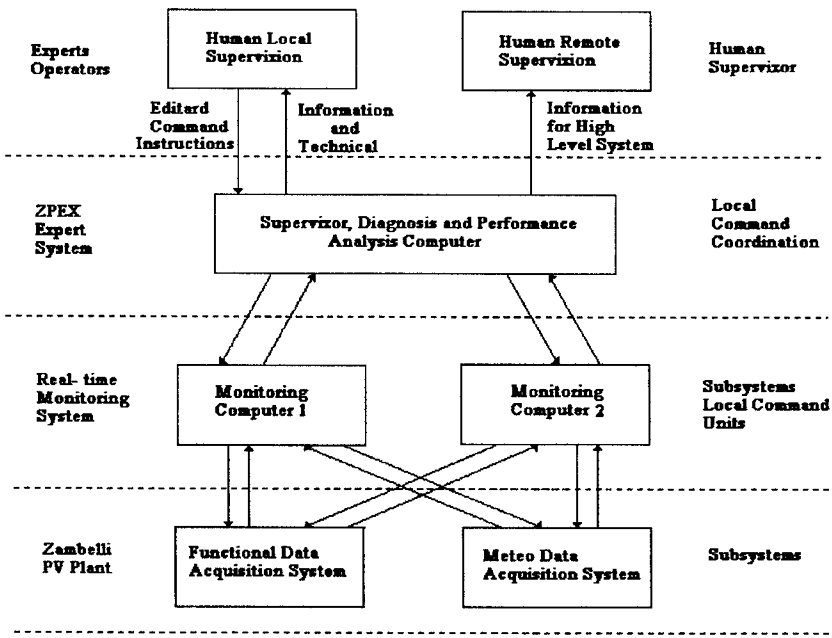

Fig. 3 – The hierarchical structure of a supervision system

ZPEX (Zambelli Plant Expert System) is a real time expert system for faults detection and diagnosis, performance analysis and consulting for appropriate counteractions destined to the operators of a PV plant. It can be included in the frame of the hierarchical man-machine concept. The acquisition of the functional data of the PV plant and of the meteorological data via sensors are under the coordination of a real- time monitoring

system. The hierarchical structure used for an automatic system is generalized towards supervision by integrating ZPEX in level 3 of the structure (see Fig. 3). This system is designated to assist the human level 4, where the local operators and remote operators (from AGSM, Verona) are included. The man-machine cooperation, in this case operator/ expert- ZPEX, is a vertical cooperation.

The design of the supervision system was performed in parallel with the design of the monitoring and man- machine systems. Thus, ZPEX became a decisional partner for the operators.

The design of the expert shells is based on an integrated approach of the design and evaluation of Zambelli PV plant supervisory system. It became with the analysis of a PV plant in order to infers functionality and its foreseen disfunctionalities. The analysis became with a bibliographic study [7], [10], followed by meetings and discussions with PV experts from AGSM, Verona and WIP Munchen [2]. Thus the technical constraints and the specific requirements were underlined. Both normal and the abnormal (degraded) functionality were analyzed. This analysis helped at the identification of the objectives to be fulfilled, taking also into account the functional necessities of the operator/expert involved in the system.

In the case of a malfunction, the degraded evolution was identified aiming at the definition of the counteractions which have to be performed by the human operator on order to limit the effects of the abnormal functionality. The method of the fault trees analysis was used in order to write a list with all the possible faults of the system, their combinations, causes and consequences. These fault trees was off- line established, taking into account the faults models, that is the behavior in case of a fault. ZPEX is an hybrid knowledge-based expert system, where both symptom and inputs based techniques (heuristic symptoms, information about the process history, statistical data and real-time acquired data by the monitoring system) and qualitative models based techniques (the rule- based representation of the system structure and behavior) were used. The rules sets were initially established for the functional modules of the system (i.e. PV arrays, inverters, batteries, etc.) and then the sets were expended by interconnections between the component modules.

The conclusions obtained from the process analysis were then used for the designed of operator/expert - ZPEX interface. The design were based on the human mechanisms used to perform the human tasks and on the analysis of the informational necessities of the operator. These lead at the implementation of a Windows based color graphical user interface, which allows:

- definition of the information displayed on- line on the screen (see Fig. 4): graphical images (explicit representation of the PV plant and the connections between its parts), acquired and calculated parameters, results of the system performance analysis (i. e. faults and their causes, etc.);
- images were structured accordingly the operational contents of the process: knowledge base editor (see Fig. 5 and Fig. 6) and real-time diagnostic system to be used in system operation (see Fig. 4);

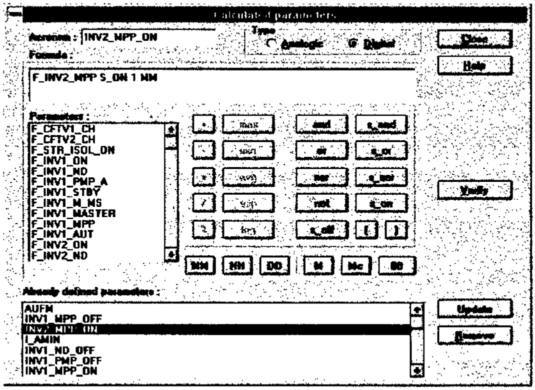

Fig. 4 - Run-time menu

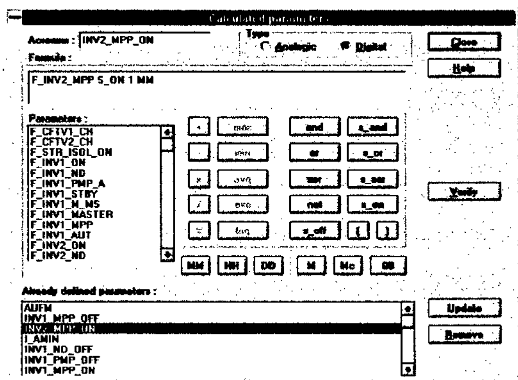

Fig. 5 - Calculated Parameters/ Menu

- definition of the necessary assistance for taking the decisions and actions (automatic alarming of the operator in case of a fault, operator's guide for limit/remove the faults, explanations of the results of the diagnosis process);
- definition of the on-line assistance for ZPEX utilization: start/stop, switch between the two operational contexts, use of the buttons/options displayed in the windows of the screen.

Some of the advantages of such a graphical interface over a command- based interface are: user- friendly interactive by graphical means, quick design of prototypes for windowing applications, and developing of program modules while reusable character. These capabilities are assured by: predefined graphical elements, predefined actions for graphical elements, and separation of the interface description from the source program.

The system implementation was performed using the successive prototypes methods: two versions were installed in Zambelli PV plant (in December 1995 and June 1996).

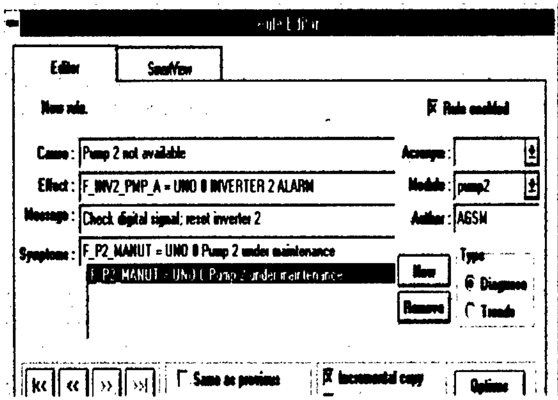

Fig. 6 - Rule Editor

Hardware And Software Requirements: The expert system for performance analysis and fault diagnosis uses the on-line acquired data of the data base built by a conventional real-time monitoring system of the plant. Personal computers became an usual support for expert systems, but memory and performance limits make them available only for small and medium systems.

The hardware configuration for expert system is a IBM compatible PC with at least: 486 DX, 66 MHz, 16 MB RAM, 350 MBB HDD, 3.5" FDD, SVGA video adapter, 14" color monitor, mouse.

The system was developed using Microsoft Visual C++ development environment and runs on Windows NT versions 3.51 or later.

Conclusions: High quality software systems is now-a-days an important request that software technology is confronted with. Expert systems are powerful tools that use artificial intelligence techniques for providing information just like a human expert would. The requests related with superior capabilities of 'reasoning' are motivated by the growing number of potential users of such systems.

A concrete implementation of an expert system based on the expert system shell described in the paper was made at the Zambelli PV pilot plant, near Verona, Italy.

Due to its flexibility this system could be used in the supervision of:

- processes in commissioning phase, normal operation, maintenance and inspection on request and teleservices and telediagnosis;
- production / products for quality monitoring and control;

- high reliable systems design for implementing re-configurable systems to be used in predictive control;
- intelligent systems.

Within the knowledge-based concept, the main difficulty is the knowledge acquisition and the lack of a founded, tried and tested theory.

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Automatic Machinery Fault Detection and Diagnosis Using Fuzzy Logic

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Abstract: Vibration based machine condition monitoring (MCM) incorporates a number of machinery fault detection and diagnostic techniques. Many of the machinery fault diagnostic techniques involve automatic signal classification in order to increase accuracy and reduce errors caused by subjective human judgment. In this paper Fuzzy logic techniques have been applied to classify frequency spectra representing various rolling element bearing faults. The frequency spectra have been processed using a variety of Fuzzy set shapes. The application of basic Fuzzy logic techniques has allowed Fuzzy numbers to be generated which represent the similarity between two frequency spectra. Correct classification of different bearing fault spectra was observed when the correct combination of Fuzzy set shapes and degree of membership criterion were used. The problem of membership overlapping found in previous studies [1], where classifying individual spectrum with respect to spectra that represent true fault classes was not conclusive, has been overcome. Further work is described which will extend this technique for application with other classes of machinery using generic software.

Key Words: Fault detection, fault diagnosis, frequency spectra, Fuzzy logic, machinery faults, rolling element bearings.

Introduction: It is well recognized that optimized maintenance practices within an industrial setting require the correct blend of maintenance strategies. Condition based (reliability centered, predictive, proactive) maintenance is an important part of this blend for many compelling reasons [2]. Condition monitoring and diagnostics is also becoming more widely recognized as an integral part of automated manufacturing systems where tool performance and product quality can be used as Computer Integrated Manufacturing (CIM) input parameters. However, detection and identification of machinery faults can be difficult in systems with a high degree of complexity. This introduces uncertainties into the condition monitoring and diagnostics activities.

Recently there has been a significant amount of research effort directed towards developing and implementing useful automated machinery fault detection and diagnostic tools. Most of these tools have been based on various pattern recognition schemes, knowledge based systems (expert systems) or artificial neural network systems. The main thrust of the work has been towards developing systems that are not only objective in

their treatment of data and presentation of results but also flexible, thereby being applicable in a wide range of situations.

Fuzzy logic has gained wide acceptance as a useful tool for blending objectivity with flexibility, particularly in the area of process control. Fuzzy logic is also proving itself to be a powerful tool when used for knowledge modeling [3] particularly when used in condition monitoring and diagnostics applications [4][5][6]. While the results reported show a degree of success, there remains a strongly subjective component to the analysis procedures. The membership functions are usually designed in a relatively subjective manner based on a preliminary inspection of the data being analyzed. The work reported on in this paper involves the use of Fuzzy logic principles in conjunction with established and accepted statistical data analysis and condition assessment standards. The procedure used is shown to be a truly objective method of categorizing vibration signals and thereby providing a means of automatically detecting and diagnosing machinery condition.

Fuzzy Logic: Fuzzy logic provides a method of reducing and explaining system complexity [3]. It deals with system uncertainties and ambiguities in a way that mimics human reasoning. It allows variables such as time, acceleration, force, distance, etc., to be represented with a degree of uncertainty. Fuzzy logic allows the membership of a variable within a group to be estimated with a prescribed degree of uncertainty. In this way, the application of Fuzzy logic to machinery fault diagnosis should allow the membership of a dynamic signal frequency spectra from an unknown source to be determined with respect to a set of spectra representing particular faults.

Fuzzy logic represents system parameters as normalized values between zero and one. The uncertainties and ambiguities associated with a system parameter can then be quantified in terms more easily interpreted by humans. For example; Is the temperature of 75°C high or low? If we know that 100°C is definitely high and 60°C is definitely low, 75°C may be considered somewhat more low than high but still not low. Fuzzy logic allows us to quantify the grey area between high and low rather than simply considering every temperature below 80°C (the mid point) to be low and every temperature above 80°C as high. So called 'crisp' boundaries are made Fuzzy but in a quantified manner. The actual degree of membership of a system parameter (temperature) in a particular group (low) is indicated by the values between zero and one inclusive. A membership of zero means that the value does not belong to the set under consideration. A membership of one would mean full representation of the set under consideration. A membership somewhere between these two limits indicates the degree of membership. The manner in which values are assigned membership is not fixed and may be established according to the preference of the person conducting the investigation.

Fuzzy sets can be represented by various shapes. They are commonly represented by S-curves, Pi curves, triangular curves and linear curves. The choice of the shape of the Fuzzy set depends on the best way to represent the data. The degree of membership is indicated on the vertical axis. In general, the membership starts at zero (no membership) and continues to one (complete membership). The domain of a set is indicated along the

horizontal axis. The fuzzy set shape defines the relationship between the domain and the membership values of a set.

The S-Curve moves from no membership at its extreme left-hand side to complete membership at its extreme right-hand side. The inflection point of the S-Curve is at the 0.5 membership point. The S-curve can also represent declining membership. It is defined by three parameters; its zero membership value (α), its complete membership value (γ) and its inflection point (β). (See Figure 1.) The domain values of an S-Curve can be determined from the following relationships [3].

$$S(x;\alpha,\beta,\gamma) = \begin{cases} 0 & \rightarrow x \le \alpha \\ 2((x-\alpha)/(\gamma-\alpha))^2 & \rightarrow \alpha \le x \le \beta \\ 1-2((x-\gamma)/(\gamma-\alpha))^2 & \rightarrow \beta \le x \le \gamma \\ 1 & \rightarrow x \ge \gamma \end{cases}$$

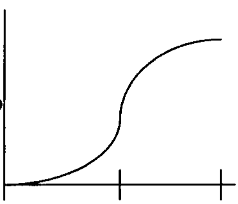

Figure 1. S-Curve

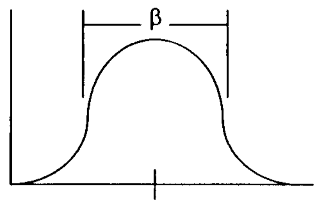

Figure 2. Pi Curve

Pi curves are the preferred and default method of presenting Fuzzy numbers where membership values have lower and upper bounds [3]. The Pi curve represents full membership at its central value. A smooth descending gradient is then observed on either side of the central value where the membership approaches zero along the domain. The parameters of the Pi curve are; the central value (γ) and the width of half of the Pi curve (β). (See Figure 2.) The domain values of the Pi curve can be determined from the following relationships where the Pi Curve is made up of ascending and descending S-Curves.

$$Pi\,(x;\beta,\gamma) = \begin{cases} S(x;\gamma-\beta,\gamma-\beta/2,\gamma) & \rightarrow x \le \gamma \\ 1-S(x;\gamma,\gamma+\beta/2,\gamma+\beta) & \rightarrow x > \gamma \end{cases}$$

The linear Fuzzy set is the simplest Fuzzy set shape being basically a straight line. For an increasing linear Fuzzy set, no membership begins at the extreme left hand side. The line then increases linearly to the position where it represents complete membership on the right hand side. (See Figure 3.) Fuzzy sets represented by triangular curves are similar to

the Fuzzy sets represented by the Pi curve. The apex of the triangle is the central value and represents complete membership. The left and right edges of the triangle represent membership that tends toward non membership in the set. (See Figure 4.)

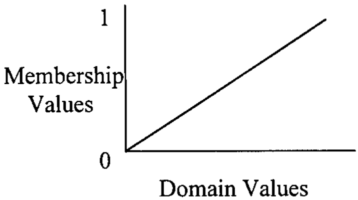

Figure 3. Linear Curve

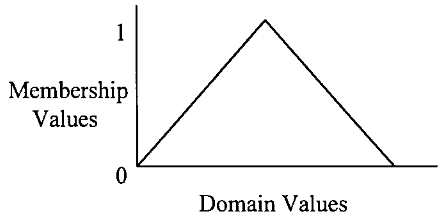

Figure 4. Triangular Curve

Signal Analysis Methodology: The aim of this work was to investigate the use of basic Fuzzy logic concepts for possible application as a machinery fault diagnostic tool. This diagnostic technique will be capable of automatic and objective machinery fault classification.

The data used in this research were frequency spectra obtained from a test rig used to conduct low speed rolling element bearing tests [7][8]. The frequency spectra obtained were representative of different bearing conditions. These bearing conditions were; No Fault (NOF), Outer Race Fault (ORF), Inner Race Fault (IRF), Rolling Element Fault (REF), Combined Outer Race and Rolling Element Faults (COM1) and Combined Outer Race, Inner Race and Rolling Element Faults (COM2). The Pi curve and the triangular curve were used to represent the frequency spectra of the various bearing conditions as members of different fault conditions. The main purpose of the investigation was to determine which Fuzzy membership curve shape worked best and to determine an objective methodology for setting the Fuzzy set membership domain limits.

Each set of frequency spectra representing different rolling element bearing faults consisted of 15 individual spectra (1 - 128 Hz). The first stage of the data analysis involved finding the mean and the standard deviation of each data set at each frequency. The average at each frequency plus or minus N times the standard deviation were the values used for the upper and lower limits of the Fuzzy membership function domains. Values of N from 1 to 10 were investigated for use with both the triangular membership functions and the Pi curve membership functions. The membership of each individual spectra was determined in relation to the average frequency spectra for a given fault type by calculating the membership at each frequency using the membership domain upper and lower limits at that frequency, adding all the membership values for each frequency together and dividing by the total number of spectral data points (128 in this case). As the upper and lower membership domain limits are changed so will the membership values for each frequency spectra.

Results: Figure 5 is an example of two typical frequency spectra derived from a dynamic vibration signal collected from a low speed rolling element bearing. (See references [7] and [8] for details of the experimental setup, data collection and signal processing.) This figure shows an outer race fault spectra and a no-fault spectra. It is clear from the figure that in this case (as well as many others) distinguishing between spectra is quite straightforward. Designing automatic diagnostic tools to work in these cases is not a problem. Difficulties arise when the differences between signals (and spectra) representing different faults are much more subtle.

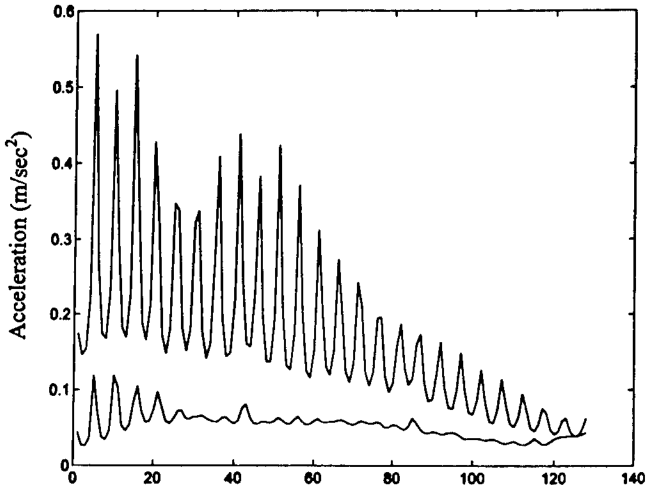

Figure 5. Outer Race Fault and No Fault Frequency Spectra.

Figure 6 is an example of two spectra representing well-developed faults of differing nature that look similar. In this case, where there is a considerable amount of uncertainty, a rigorous and finely tuned automatic diagnostic tool is required. Not only are individual samples of frequency spectra representing different faults often rather similar, but the variability within a group of spectra that represent the same fault is often significant. Figure 7 shows 15 frequency spectra that represent the same sample fault. The challenge is to prc ʼide early detection capability as well as distinction between fault types with a low risk of false alarms.

Figure 8 shows the average of the 15 different frequency spectra shown in Figure 7. Also shown are the limits that represent 2.5 standard deviations above and below the average spectra. The standard deviations were calculated at each frequency (1 to 128 in this case). This figure shows the variability within a group of frequency spectra representing one type of bearing fault condition. Similar degrees of variability exist within other fault types.

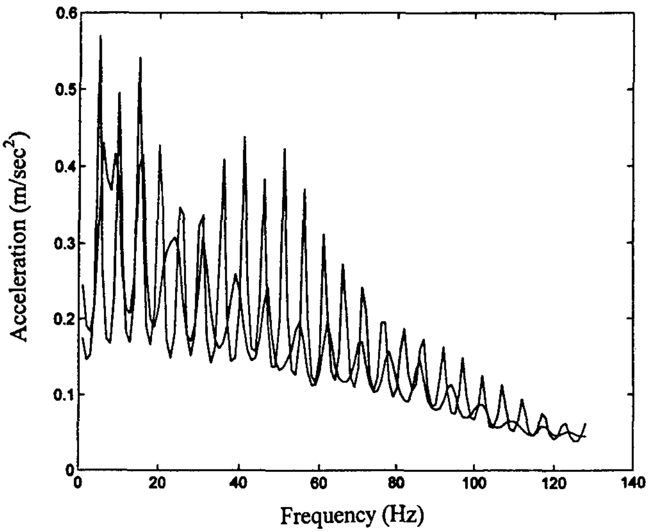

Figure 6. Outer Race Fault and Inner Race Fault Frequency Spectra.

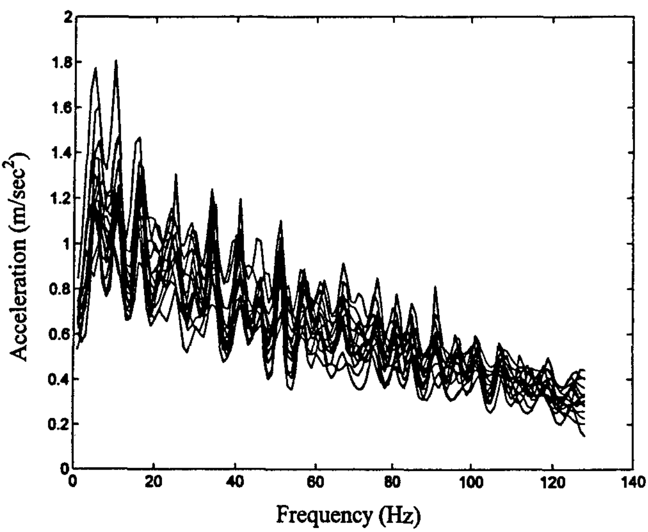

Figure 7. Frequency Spectra from 15 Different Vibration Signals (Representing COM1 Type Fault)

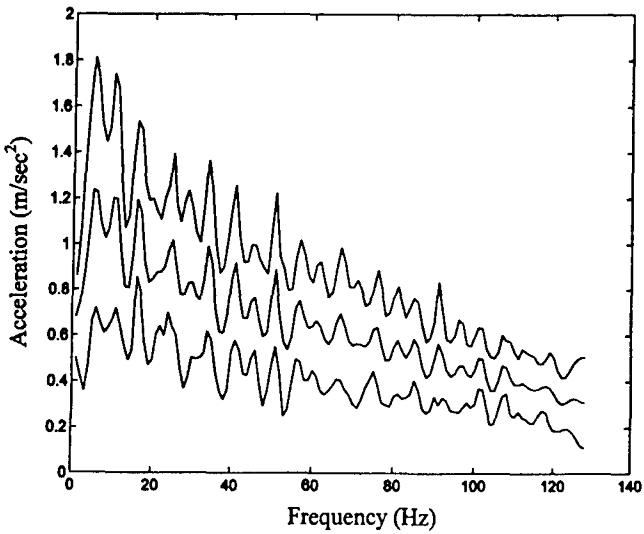

Figure 8. Average COM1 Spectra and ± 2.5 Times the Standard Deviation at each Frequency

In order to optimize the Fuzzy diagnostic scheme the upper and lower Fuzzy membership function domains used were set to match different multiples of the standard deviation at each frequency. Each pair of membership domain limits were then dependent on the standard deviation of the frequency spectra at each frequency rather than being set arbitrarily.

In order to determine the best membership function shape and domain value limits a broad range of values were trialed for both the triangular membership function and the Pi-curve membership function. Table 1 shows a sample of the results from the triangular membership function trials. In this table the results are shown from a trial where a frequency spectra representing an outer race fault is compared to all the other fault types. A variety of multiples (N = 1, 2, 3, 4, 5, 10) of the standard deviations derived at each frequency for the given fault spectra were used as the Fuzzy membership domain limits. The same comparisons were made with all the frequency spectra. Table 1 shows a representative sample of the overall results. From these results it is evident that even when extending the upper and lower membership function domain limits to 10 times the standard deviation, a clear diagnostic trend does not develop. In fact, the distinction between a correct classification and the incorrect classifications in most clear at membership function limits of 2.0 times the standard deviation.

Table 1: Triangular Domain Function Results
(Outer Race Fault versus Other Fault Types)

FAULTS	N (multiples of standard deviation) 1	2	3	4	5	10
NOF	0.015	0.034	0.075	0.159	0.275	0.621
ORF	**0.359**	**0.611**	**0.737**	**0.803**	**0.842**	**0.921**
IRF	0.171	0.335	0.471	0.571	0.645	0.815
REF	0.132	0.275	0.407	0.518	0.601	0.788
COM1	0.0	0.0	0.003	0.007	0.017	0.058
COM2	0.0	0.0	0.002	0.005	0.008	0.039

Figure 9 is a sample bar chart of a self test classification trial conducted with all the frequency spectra correctly grouped into the different fault categories and Pi-curve membership functions. It shows that the likelihood of correct classification of any sample increases continuously with increasing membership function domain limits. An optimum efficiency is reached at four times the standard deviation. Narrower or broader limits reduce the possibility of correct classification. Using narrower limits mean fewer spectra representing a given fault type would fit that classification, while using wider limits would allow spectra representing other fault types to be classified into the class under consideration.

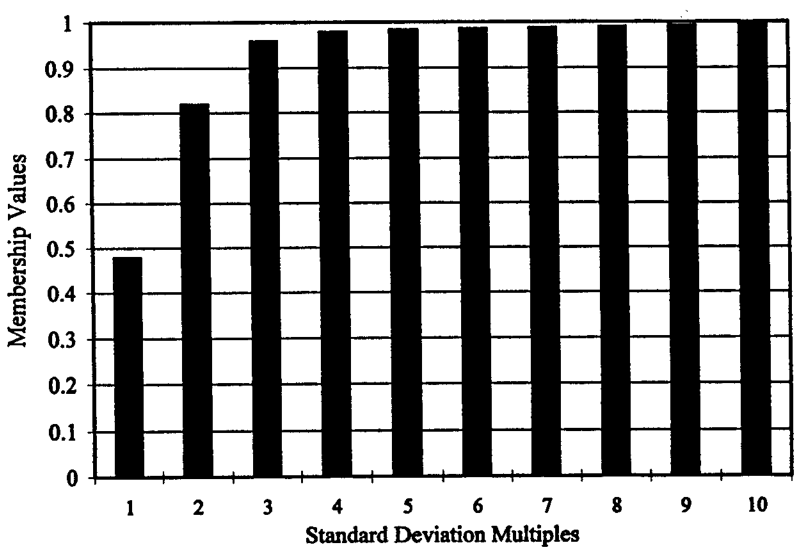

Figure 9. Sample Self Test Classification Trial
(Outer Race Fault, Varying Membership Function Limits)

Using membership function domain limits of four times the standard deviation, a cross-classification trial was conducted. Table 2 shows the results of this trial. The ability of this procedure to correctly classify frequency spectra representing different fault classes is clearly shown.

Table 2: Pi-Curve Domain Function Results

	N = 4 × Standard Deviation					
FAULTS	NOF	ORF	IRF	REF	COM1	COM2
NOF	**1.0**	0.204	0.224	0.459	0.001	0.0
ORF	0.088	**1.0**	0.499	0.551	0.031	0.0
IRF	0.102	0.560	**1.0**	0.682	0.013	0.0
REF	0.159	0.500	0.478	**1.0**	0.021	0.0
COM1	0.0	0.117	0.0	0.006	**1.0**	0.239
COM2	0.0	0.008	0.0	0.001	0.5218	**1.0**

Discussion: Linear curves, triangular curves, S-curves and Pi curves are the common membership set shapes used to represent data when using Fuzzy logic. In this study, where membership functions with upper and lower limits were required, the triangular curves and Pi-curves were used. These Fuzzy membership functions were used to classify individual frequency spectra representing different rolling element bearing fault conditions.

A trustworthy and truly objective procedure is required for the task of fault diagnosis because of the variability of different individual frequency spectra representing the same fault condition. Different frequency spectra often have similar general characteristics but may vary considerably depending on the data collection procedures followed and the machinery operating conditions during data collection. Human analysts tend to make subjective judgments that may also vary from day to day and from analyst to analyst. Figure 5 through Figure 8 shows the actual degree of variability that is common.

As described in the results section, the Fuzzy membership function upper and lower domain limits were set using a range of multiples of the standard deviation as calculated for each class of fault spectra. The optimum limit values were then sought using self test classification and cross-class classification trials. The self tests were conducted by correctly classifying a particular frequency spectra using different Fuzzy membership function domain limits. The limit that gave consistent correct classifications was considered to be the optimum.

The triangular membership domain limit results and the Pi-curve membership domain limit results both showed that as the upper and lower limits were increased the likelihood of particular frequency spectra being classified with a high degree of membership into the group where it belonged (correct classification) increased. However, the likelihood of similar spectra, belonging to other fault classes, being incorrectly classified also increased.

For the tests involving the triangular membership function it was found that a clear diagnostic trend, or optimum membership domain limit value was not reached. The

maximum distinction between correct and incorrect classification existed at membership domain limits equal to two times the standard deviation.

The tests involving the Pi-curve membership function did show a clear diagnostic trend with the optimum membership domain limit values being reached at four times the standard deviation. Narrower or broader limits acted to reduce the possibility of correct classification. Using narrower limits mean fewer spectra representing a given fault type would fit that classification, while using wider limits would allow spectra representing other fault types to be classified into the class under consideration. Table 2 shows the results of an example cross-class classification trial where the clear distinction between correct and incorrect classification is obvious. This result is possibly due to the similarity of the Pi-curve shape to the approximately Gaussian distribution that has been shown to exist in statistically stationary data collected from rotating machinery.

Concluding Comments: This work has investigated the use of basic Fuzzy logic techniques as a machinery fault diagnostic technique. The work conducted has displayed the potential of Fuzzy logic to classify frequency spectra according to the likely fault condition which they represent. Its ability to classify and identify machinery faults shows considerable potential. Using membership function domain limits that that are linked to the variability of a group of spectra, that represent a particular fault type, at each frequency within the spectra allows the technique to be truly objective. This work outlines the procedure for arriving at this objective technique. The optimum limits were found manually in this study but this process could also be easily automated. Future work will focus on the task of developing generic software that will be able to import and process data from a variety of sources and representing a variety of machinery types.

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Masking Water When Using a Laser Particle Counter

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Abstract: The interaction of a water droplet with the sensor of a laser particle counter causes the water droplet to be measured as a (solid) particle since the droplet obscures at least a portion of the light. Thus when using a laser particle counter both water and solid particles are counted as contaminants. There are advantages for knowing both the concentration of water in an oil sample and the concentration 'solid' particles. Moreover, situations arise when it is advantageous to know the true concentration of solid particles when using a laser particle counter. This paper outlines a method for masking water and obtaining the solid particle content in an oil sample. The paper discusses theory and provides a procedure used for masking water in mineral oils (and also polyalphaolefins, PAO). A 1:1 mixture of mineral oil and mixed solvent (mixed solvent = 3 parts toluene and 1 part isopropanol) effectively eliminates water concentrations up to 10,000 ppm in oil. The mixed solvent essentially dissolves water present while still being soluble in mineral oils. A similar solvent mixture has been found effective in masking water in glycol based oils.

Key Words: Laser particle counter; lubricant contamination; water.

Introduction: The interaction of a water droplet with the laser sensor system in a particle counter causes the water droplet to be measured as a (solid) particle. There are advantages for knowing both the concentration of water in an oil sample and the concentration of 'solids'. However, situations arise when it is advantageous to know the true solid concentration when using a laser particle counter. This paper outlines a method for masking water in the laser particle counter and obtaining the solid content of the oil sample. The procedure should also work with a white light particle counting system. This paper discusses the procedure used for mineral oils (and also polyalphaolefin PAO). A similar procedure has also been found effective in water contaminated polyalkylene glycols (PAGs). It is not known if this procedure is effective with water contaminated polyol esters (POEs), but it will likely be effective.

Water in oil: Water and oil do not mix, but water has a small but finite solubility in mineral oils - we refer to this as dissolved water. At room temperature, the solubility of water is about 20 ppm for a transformer (paraffinic) type oil and 200 ppm for an oil with a large aromatic (napthenic) content. Dissolved water in mineral oil does not present an interference in a laser particle counter because it is homogeneously dispersed throughout the system. The solubility of

water in oil approximately doubles for every 25 ^{0}C temperature increase. The presence of an additive package will increase the solubility of water in oil as well. Conversely, if the oil cools (after operation) then dissolved water may form free water in the system. The ambient humidity level also affects the amount of water in oil, but this only occurs over long (weeks to months) period of time. Low humidity levels may cause the amount of water to decrease in the system whereas high humidity may increase it.

While dissolved water in oil is relatively benign, free water is almost always deleterious. Free water may be emulsified or non-emulsified. Free water can often be detected by a hazy or cloudy appearance of the fluid. It is free water that obscures light in the laser particle sensor and is therefore detected as a 'particle'. It is also free water that causes numerous problems in oil system machinery. Free water may cause galvanic corrosion between dissimilar metal parts and certain metals (particularly copper and iron), and may promote the corrosion of the system. Copper and iron are particularly good catalysts for oxidizing oils. Furthermore, some metals in the presence of water enhance the oxidation of the base stock of the lubrication oil. Lube oil oxidation products produce precipitates that form varnishes and resins causing poor lubrication and fouling the filtering system. Free water may react (hydrolyze) with antiwear additives such as ZDDP (zinc dialkyldithiophosphates) to form hydrogen sulfide, which ultimately oxidizes to sulfuric acid. Finally, oil and water make a good environment for harboring microbes. Microbes digest and oxidize the oil producing organic acids which cause corrosion.

One simple procedure for determining the presence of water in oil is the crackle test. If the sample crackles when heated above the boiling point of water, it indicates the presence of water. However, this test does not indicate the quantity of water. The industry standard for measuring water in oil is the Karl Fischer reagent method (ASTM D-1744). This method is considered accurate to 10 ppm. One problem with the Karl Fischer reagent is that it reacts with certain additives (for example ZDDP) present in the oil, although procedures exist to circumvent this difficulty. The laser particle counter user may wish to correlate the results using the procedure outlined in this paper with laboratory Karl Fischer water determination. That is determine the amount of water present in the oil sample with Karl Fischer test results, then compare the amount of particles that are eliminated during the masking procedure. The data may be used for screening oil samples and determining which need further laboratory tests, while giving more quantitative results than the crackle test.

Procedure and theory: Since water and oil do not mix, the trick is to find a solvent system that dissolves both water and oil. A solvent like isopropanol (also known as 2-propanol or rubbing alcohol) is miscible (dissolves) in water in all proportions. Unfortunately, isopropanol is not soluble in oil. A solvent like toluene is soluble in oil in all proportion, but does not dissolve very much water. However, toluene is soluble in isopropanol, because both are small organic molecules [1]. Moreover, a mixture of three parts toluene and one part isopropanol is soluble in mineral oils. The toluene is used to dissolve the isopropanol and the mixture becomes soluble in mineral oil, the isopropanol then dissolves any water present in oil. The result is a clear oil solution without the cloudy haziness characteristic of water suspension in oil.

Toluene and isopropanol are cheap solvents available from chemical supply companies. The preferred ratio (3 parts toluene to 1 part isopropanol) is based on laboratory experiments perfecting this technique. A smaller ratio of isopropanol is insufficient for dissolving water, while a larger ratio causes the isopropanol to segregate to the emulsion (that is there is insufficient toluene to dissolve the isopropanol into the oil, so it segregates to the water phase).

A 1:1 mixture of oil and mixed solvent (mixed solvent = 3 parts toluene to 1 part isopropanol) effectively eliminates water concentrations up to 1% (10,000 ppm) in oil. No dilution of the oil sample with kerosene is required. Note that the oil sample containing mixed solvent is considered hazardous waste and must be disposed of properly. A mixture of isopropanol/kerosene or isopropanol/mineral spirits also will dissolve water in oil. However, these two alternate solvent systems are not as effective when the water concentration is large.

The user will have to run a background particle count for the solvent system, and then correct for this background count and the dilution of the hydrocarbon oil when calculating the number of particles in the system.

Apparatus

1. Laser particle counter or white light particle counter.
2. Balance
3. Filtering device with 0.8 micron filter
4. Vacuum chamber for degassing air bubbles (desiccator and vacuum pump is adequate)
5. Beakers and containers

Reagents

1. Toluene
2. 97% pure or better isopropanol (also known as 2-propanol or rubbing alcohol)

Procedure

1. Thoroughly clean and dry the beakers and containers to be used. Remember, containers may be a source of particle contamination.

2. Prepare the mixed solvent. Weigh three parts of toluene (density = 0.867 g/ml) with one part isopropanol (density = 0.786 g/ml). The routine user may wish to prepare a gallon or more of the mixed solvent. Filter the mixed solvent through the 0.8 micron filter.

3. Run the mixed solvent through the particle counter to obtain the diluent background count. If the background count is large clean a new container and filter again.

4. Determine if the oil sample contains free water (frequently a hazy or cloudy oil sample indicates the presence of emulsified or free water). This can be verified with a crackle test. Alternatively, the user can run the oil sample (preferably diluted with kerosene) through the particle counter using standard procedures. If the number of particles at 2 and 5 microns are approximately equal, this may indicate the presence of water.

5. Weigh a 1:1 mixture of oil and mixed solvent. Vigorously shake the oil sample to ensure the suspension of large particles. Degas the oil sample in the vacuum chamber to remove air bubbles. Immediately run the mixed solvent diluted oil sample through the particle counter.

Discussion

Figure 1 is a plot of ISO code versus particle size in an experiment performed using a laser particle counter. The original oil sample (see graph) contained an ISO code cleanliness level of 17 at 2 microns and falls to a code of 10 at 25 microns. The oil sample was spiked with 10,000 ppm water and shows a cleanliness code of 24 at 2 microns and falls to a code of 19 at 100 microns. Note the 'flatness' of the line which indicates the presence of water and saturation of the particle counter. The 10,000 ppm oil sample was treated with a 50:50 mixture of the recommended mixed solvent. The mixed solvent oil sample now shows a cleanliness code very close to the original sample, indicating the effectiveness of this procedure in eliminating water interference in the laser particle counter. We have performed numerous experiments similar to this example that show the usefulness of this technique.

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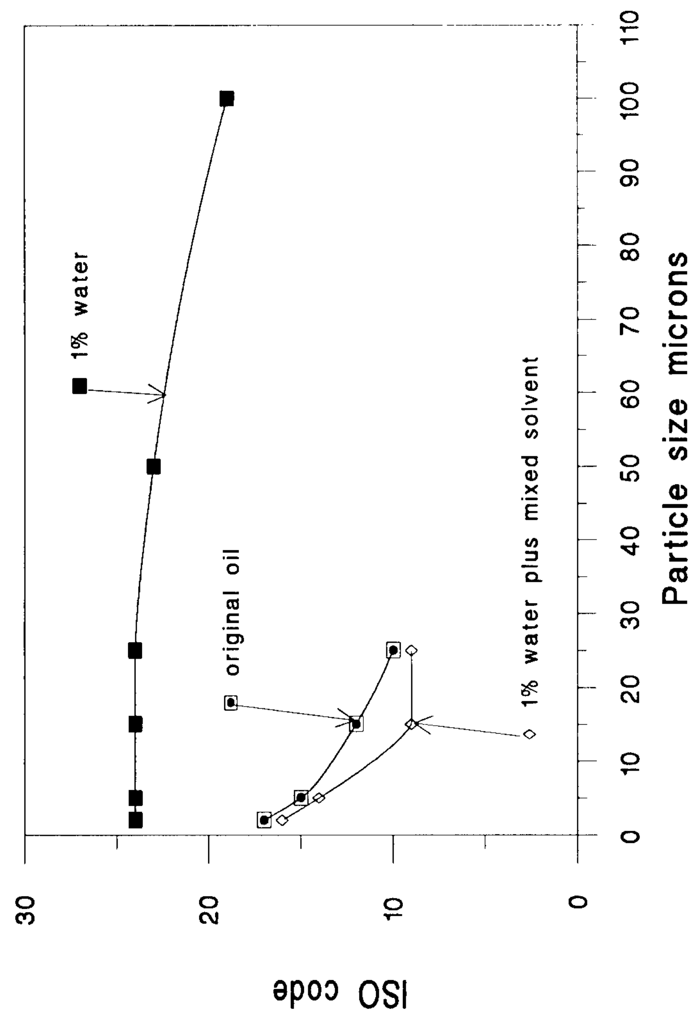
ISO code
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
110
Particle size microns
1% water
original oil
1% water plus mixed solvent

CONVERTING TRIBOLOGY BASED CONDITION MONITORING INTO MEASURABLE MAINTENANCE RESULTS

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Abstract: An effective industrial tribology program is much more than just oil analysis. Oil analysis reveals important information about the condition of machinery, lubricants, and contamination in the lubricants. Substantial savings are achievable through an effective oil analysis program. However, much greater benefits are achievable through a reliability based tribology program such as:

- improved capacity by avoiding breakdowns,
- known condition of equipment – thereby providing status of plant capacity,
- integrated with other condition monitoring technologies,
- improved overall indication of system health,
- employment of value based application of tribology technologies,
- achieved optimum selection of lubricants,
- application of contamination control and established cleanliness for systems,
- achieved machine and lubricant life extension,
- realized failure reduction through root cause analysis, and
- applied quality assurance for lubricants, filters, breathers, refurbishment, etc.

Key Words: Tribology, industrial oil analysis, benchmark, minilab, failure, abrasion, fatigue, adhesion, chemistry, contamination, wear, trivector, best practices.

Introduction: Tribology can be defined as the study of surfaces in relative motion. This multifaceted science addresses friction, lubrication, and wear, which are fundamental in nearly all mechanical systems. Each of these has major cost impacts within industrial plants.

For example, friction within mechanical systems directly translates into power loss. Lubrication costs include procurement, storage, filtration, installation, recycling, and disposal. Wear is the primary characteristic defining the end of life for plant machinery and leads to costs of maintenance, replacement, and production outage. Friction, lubrication, and wear are interactive and cannot be separated. A successful tribology program necessarily addresses all three elements from the perspective of their total cost to the industrial plant.

Oil analysis programs for industrial plants have been reported to save $277,000 per year from extended oil drain intervals, avoided maintenance actions, and production uptime. The benefits from this more comprehensive approach have been documented as well over $1,000,000 per year for very large plants and are classified as follows: 70% equipment failure, 20% lubricant procurement, 5% material handling, and 5% electrical power. See references 6, 9, 10, and 16.

Industrial Fluid Analysis: Oil analysis of used lubricant and hydraulic fluid samples reveals deterioration or breakdown of the fluid, contamination of the system with water or particulate debris, and wear of the lubricated machinery. Oil analysis can be done on-site, by the reliability maintenance team, or off-site by a contracted fluid analysis laboratory There are reasons, summarized in this report, why plants should do both of these

In either case, it is important to understand that analysis of used lubricants is done to gain insights as the condition of the lubricant, the amount and types of contamination, and the health of the machine from which the fluid samples are taken Substantial cost savings can be attributed to each of these factors.

The value of this information can only be realized if it can be collected and analyzed in a timely and organized manner. This is best done using a multilevel computer database that is logically organized based on proximity or types of machinery. Each database will include "oil routes" which identify a sequences for collecting oil and hydraulic fluid samples

Further benefits are achieved by making more complete use of computerized tribology information as follows:

- samples scheduled automatically on condition,
- computerized trending and record keeping,
- knowledge based expert system assists with data interpretation,
- electronic link to lab,
- direct link with CMMS, and
- full integration of condition monitoring technologies.

In addition to analysis of used lubricants, the best tribology programs address the selection, procurement, storage, handling, monitoring, recycling, and disposal of these critical fluids as they are used throughout the plant. They initiate maintenance actions "on condition" rather than on a calendar basis whenever practical. They have management practices that effectively and efficiently collect tribology information, and support its influence within maintenance, operations, production. They take a proactive approach to maintenance, employing root cause failure analysis and contamination control measures.

Those plants following best practices for tribology will integrate the concept of profiles into their lubricant analysis activities. Each class of equipment has different loads, speeds, wear out and failure mechanisms from other classes. As such, each class fits into a profile for inspection, sampling, and analysis. This way, the analysis matches the requirements of the application.

Procurement Practices: Another "best practice" characteristic involves emphasis on the procurement of quality lubricants with ongoing quality assurance and quality control for lubricants, filters, and breathers. This is best done through a partnership relationship with lubricant and filter suppliers, understanding that the plant will continually review these products for their applicability and value.

Tribology as a part of Multi-Technology Condition Monitoring Team. Within the condition monitoring team, the vibration diagnosticians need to be equally comfortable with tribology, having a good understanding of lubrication technology. Best practice means incorporating preventive, proactive, predictive philosophies, utilizing full cost-benefit analysis to select the best combination of these. The underlying objective in each of these areas is the continuous reduction of lubrication costs, reduction of lubricant related maintenance costs, and increased production up-time.

Preventive Maintenance. Preventive maintenance includes interval based maintenance activities whose goal is to periodically inspect machines, add fluids, adjust components, replace parts, and overhaul machines based on the statistical likelihood that these actions are needed at just that interval. The interval for preventive maintenance is too soon if problems being addressed have not had sufficient time to develop. The interval is too late if failure modes have initiated and shortened design life of the machine. Since the latter situation is more serious than the first, and since the true condition of the machine is not known, preventive maintenance intervals are normally set at conservatively short periods.

Periodic inspections, oil sampling, and Calendar based oil change are three examples of tribology practices which fall into the category of preventive maintenance. The first two of these are intended to collect machine condition information which serve as a basis for proactive and predictive activities. The third, however, should be questioned. If the cost and impact of too frequent oil changes are small, then machine hours or Calendar days may be the most practical basis for initiating oil change work orders. However, Calendar based oil change is almost certainly being done either too soon or too late; too soon if the oil has remaining useful life, and too late if it is badly contaminated.

Proactive Maintenance. Proactive maintenance includes condition based maintenance activities which aimed at machine life extension as opposed to failure detection or breakdown prediction. This includes root cause failure analysis together with associated corrective measures. Proactive maintenance targets mechanisms leading to failure and eliminates them. When this is done properly, machine life can be doubled or even tripled.

Elimination (1) of deteriorated oil or (2) of excessive contamination or (3) of improper machine operating conditions (misalignment, imbalance, looseness, rub, etc.) are three good examples of tribology proactive maintenance practices. Independently, these conditions lead to physical wear and reduced machine life. When combined, these conditions are synergistic causing rapid machine deterioration.

Predictive Maintenance. Predictive maintenance includes condition based maintenance activities intended to non-intrusively predict remaining operational life of a mechanical system. This is typically done by monitoring the progression of failure from conditional (root cause) to incipient (initiated and in progress) to impending (significant damage) to precipitous (impaired) and finally to catastrophic (inoperable).

Tribology predictive maintenance practices view progressive states of wear deterioration to ascertain the remaining operational life in the machine. These include sampling and testing oil to measure and classify wear debris in the oil. The actual prediction of catastrophic breakdown of the machinery is normally best done using vibration analysis in conjunction with oil analysis

Elimination of Root Causes of Failure. Machines can breakdown at any time, however, the reasons for breakdown typically fall into one of three time dependent categories: (1) start up, (2) random, and (3) wear out. Startup failures are those which occur within a short time after original equipment installation or within a short time after repair. Random failures occur at any time, regardless of machine life. Wear out failures determine the normal life of machinery and result from progressive deterioration of components which are subject to wear, aging, or chemical attack. After studying the causes and frequency of failure, the condition monitoring team can recommend investments be made in appropriate proactive measures to minimize or even eliminate these causes.

Startup Failures. Root causes of startup failures include improper assembly or installation, built in contamination, defective components, or machine design deficiencies. Most of these can be attributed to either the original equipment manufacturer or to the equipment installation team Therefore, the controls to reduce startup failures are best implemented through improved contractual specifications:

- functional design specifications,
- startup and inspection before delivery,
- ISO cleanliness requirements,
- precision alignment and balance requirements,
- after installation startup and inspection, and
- cleanliness monitoring and removal of break-in wear debris.

Random Failures. Root causes of random failures can be elusive. The word random implies that one cannot find a common mode of systematic failure. Nonetheless, all failures have causes; and even when the causes are isolated and unusual, one can normally find contributing factors which can be minimized or eliminated. Failures tend to be synergistic. This is to say that two independent causes combined together are much worse than either one independently. It is reasonable to expect that when practices implemented to minimize both start up and wear out failure modes, then random failure modes will also be greatly reduced.

Wear Out Failures. Root causes of wear out failure include a synergistic combination of the environment, mechanical loads, and surface chemistry. Environmental factors affecting machine life include heat, dust, and water contamination. Mechanical loads can be acceptable or excessive, depending on machine operation, balance, shaft alignment, etc. Surface chemistry for oil wetted surfaces can be benign or under chemical attack, depending on the condition of the lubricant and presence of corrosive fluid contamination.

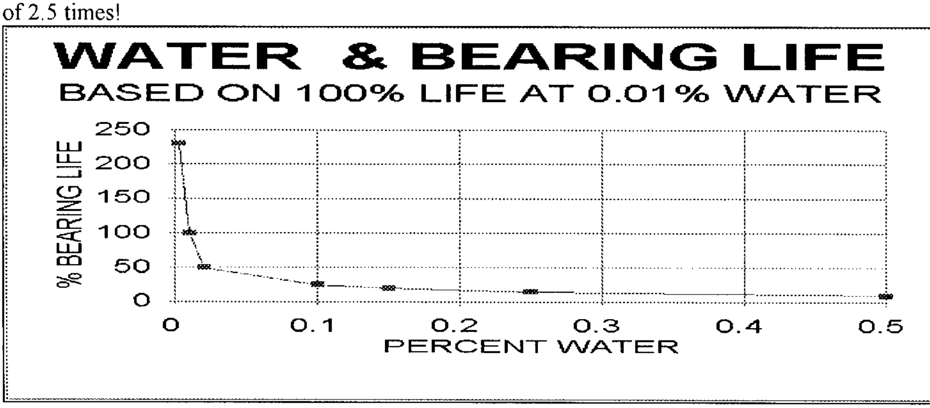
The combined effect of these environment/machine/chemistry factors results in physical wear. The following list shows seven basic lubricated wear mechanisms listed in percentage order:

- abrasive wear due to particulate contamination (46%),
- fatigue wear due to cyclic loading (17%),
- adhesive wear due to machine design tolerances (13%),
- corrosive wear due to contamination with moisture and air (9%),
- fretting wear due to chemical attack combined with oscillating motion (9%)
- erosive wear due to particulate contaminants (6%), and
- cavitation wear due to implosion of bubbles (<1%).

Principle Root Causes of Failure. There are seven principal root causes failure which promote wear in mechanical systems. An effective tribology program will take action to control the impact that each of these has, particularly on critical plant machinery.

- fluid contamination,
- fluid leakage,
- chemical instability,
- cavitation,
- temperature instability,
- wear,
- material distortion or misalignment.

Contamination Control. Contamination of the lubricant or hydraulic with leads directly to reduced component and machine life. For example, the Timken Bearing Company report that the effect of water on bearing life is shown on the attached graph. Notice that reducing water contamination from 0.01% (100 ppm) to 0.0025% or (25 ppm) increases bearing life by a factor of 2.5 times!



The SKF Bearing Company report that if contaminants larger than the clearances between bearing elements are filtered from the system, the bearing can effectively have infinite life!

The British Hydraulics Research Association reports that if the solid particle contamination in an operating system can be reduced from ISO 20 to ISO 15 for particles larger than 5 microns, then machine life will be increased by five times!

Contamination control, for both water and solid particle contamination, is a proven method to extend machine life, and reduce both start up and random failure occurrences

Target Cleanliness Levels (TCLs) need to be established for both water and for solid particle contamination in lubricant and hydraulic system. The units TCL for water are in percent or ppm. The TCL units for solid particles are typically given as ISO or NAS code values.

In general, high pressure systems (e.g., hydraulics) have much greater sensitivity to small amounts of water and wear debris than low pressure systems (e.g., lubricants). TCLs are set based on the most sensitive component within the system. Filter companies and original equipment manufacturers have published recommended TCL values for particle contamination The TCLs for water contamination are best set by monitoring plant systems and taking all reasonable steps to minimize moisture in lubricant and hydraulic systems.

Oil Analysis. Analysis of oil for maintenance purposes can be compared to analysis of blood for medical purposes. In both cases the fluid contains valuable information that can be revealed through testing. Sometimes one test gives all the needed information, other times, an entire battery of tests is needed. Some tests are simple and inexpensive Others are elaborate and expensive. So which tests get run for a particular sample? What instruments are used? What is the purpose?

Addressing these questions beginning with the last, what are the purposes for oil analysis? Just about any test done on new and used lubricants are intended to find out one or more pieces of information about three conditions: (1) the condition of the lubricant, (2) the state of cleanliness (absence of contamination) for the lubricant system, and (3) the health of the oil wetted machinery. A range of tests can be conducted to fully explore every one of these conditions, however it is not practical to do them all on all equipment So how does one select which test to run and what equipment or method should be used?

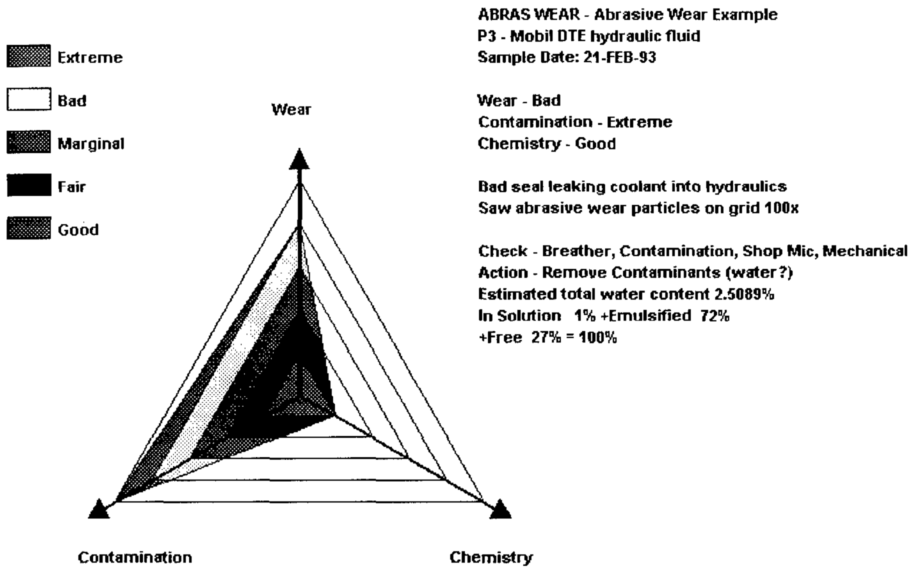
As stated earlier, there are a variety of tests one can perform to measure each of these parameters. The appropriate tests are selected giving consideration to the relative benefit and cost of each.

Almost any lubricant or hydraulic fluid sample can and should be tested on-site by the condition monitoring team. On-site oil analyzers are capable of measuring lubricant quality, solid and liquid contamination, and mechanical wear debris. At the same time, more detailed and comprehensive analyses are available off-site from a qualified fluid analysis laboratory.

Although oil analysis appears to be complex, it really is quite easy to understand. The primary thing that makes it appear difficult is probably confusion over what the numbers mean. The results of oil analysis are in widely different units such as mg-KOH, parts-per-million,

dimensionless index units, absorption at a wave number, mg/L, and many more. A convenient representation has been developed to bring all this complexity back into a simple to recognize diagram. This 3-dimensional representation of all available oil analysis results, whether from an off-site lab or an on site "minilab," is called the "Trivector" and is shown in the following figure.

In this figure, the x-, y- and z-axis each represent chemistry, contamination and wear respectively. Each axis is normalized using the relative alarm levels for each different measurement parameter. Graphic illustration is supported by text and numeric information to give the user a status-at-a-glance understanding for the sample.



On-Site Oil Analysis. In-shop, in-house, and bench-top are all terms that have been used in reference to on-site oil analysis. This form of testing can and should be done by the condition monitoring team. It should be in the same general area of the plant where the people who do vibration analysis, shaft alignment, and balancing are located. On-site oil analysis realizes the following benefits:

- ownership and control,
- immediate results with immediate retest when needed,
- analysis is done by the people who know the most about these machines,
- electronic data with no transfer,
- test more points more often,
- test incoming lubricants, and
- find, fix, and verify problems are fixed all in same day.

The first step in on-site oil analysis requires no special instrumentation It is as simple as look, smell, touch, and think. The condition monitoring technician or plant oiler who is equipped only with familiarity of the fundamentals of tribology can add significant value to the program

SKF report that 75% of all bearings fail because of inadequate lubrication and another 24% fail due to irregularities in the environment such as improper installation Many of these failures can be avoided by looking at fluid sight glasses, and by using the right tools and techniques for handling, storage, and installation of bearings.

Quantifiable and highly sensitive measurements of lubricant properties, contamination levels, and wear conditions are also available through on-site oil analysis. A variety of instruments are designed to provide the plant condition monitoring team with partial to comprehensive analysis capabilities.

- either individual or multi-functional oil analysis instruments capable of quantitatively measuring lubricant degradation, water contamination, and iron wear debris,
- in-shop wear debris analysis tools including a microscope,
- in-shop viscometers to identify misapplication of lubricants and fluid or gas contamination,
- field rugged particle counters to measure particulate contamination, and
- automatic ferrographic instruments suitable for rapid automatic measurement of total iron content.

The best programs typically start small and grow. The best practice, continuous improvement plan should be laid out with the intent of building a "minilab" appropriate for on-site oil analysis. All of the on-site instruments are should operated from the software. This software should have full database and reporting capabilities. Those who use both vibration and oil analysis should expect full integration of these complementary technologies within a single data structure and within the same software.

Off-Site Oil Analysis. Fluid analysis and consulting services should be obtained from an qualified industrial fluid analysis laboratory. This section outlines the ***minimum*** capabilities for a suitable industrial fluid analysis laboratory including:

- Spectrometric oil analysis (SOA) including rotrode spectroscopy,
- Viscometry at 40 C and 100 C,
- Infrared Spectroscopy (FTIR),
- Wear debris analysis,
- Total Acid Number (TAN),
- Water by Karl Fisher, and
- Particle counting with true size distribution.

<u>Measuring Performance – Typical Metrics.</u> Financial metrics are needed to gage the effectiveness of a tribology program. The first step is to establish a baseline for comparison in future years. This is essential in some plants for the long term success of the tribology program. This is because the marginal savings from year to year reduces as the program approaches industry benchmark status. All too often, management loses sight of the major savings achieved when the tribology program was first implemented. Then in lean years, budget cuts take short-term savings, allowing the plant to slip back into poor tribology practices and associated costs.

Measure Equipment Failure Avoidance. This category typically accounts for 70% of the total tribology program cost savings. Two approaches are used to measure savings from equipment failure avoidance: (1) case-by-case, and (2) class-by-class. The total cost savings for equipment failure avoidance is the sum of these two, taking care not to double count.

Measure Case-by-Case. These savings are documented on a case-by-case basis using CSI's compile case histories. Tribology equipment failure avoidance case histories are commonly triggered by one of two events: extreme wear condition or extreme lubricant contamination from water, coolant, or process materials detected in the lubricant.

For example, a rotary vane mechanical pump costs $16,000 to replace. This particular pump is water cooled. On-site analysis revealed extreme amounts of water and large wear debris in the oil. Unnoticed, it is reasonable to assume that this pump would have failed under this condition. Pump seals and bearings were replaced at a cost of $1,000. Since a backup pump was available and operational, no credit is taken for loss of production. Cost avoidance in this case is $16,000 - $1,000 = $15,000.

Measure Class-by-Class. These savings are documented on a class-by-class basis through grouping similar equipment into class groups. It is suggested that the condition maintenance team identify the 5 most common classes of equipment in the plant. Do not attempt to group all plant equipment into these classes, only group the same kinds.

For example a power plant uses 27 similar coal pulverizers which were grouped together into one class. Maintenance and repair histories for these pulverizers can then be studied and trended. In this particular case, pulverizers followed scheduled maintenance and overhaul. Typical overhaul of the main bearings cost $10,000. Unscheduled failures, or breakdown occurred at the rate of 3 or 4 per year.

A tribology condition monitoring program was implemented such that overhauls were done on condition rather than on schedule. Statistical alarms were used including all 27 pulverizers. Those falling at the upper end of the statistical range (e.g., those with the highest 20%) received corrective actions. Those with high Corrosion, OilLife, and Contaminant indexes received oil changes and seals were inspected and replaced as needed. Those with highest ferrous index values were torn down for overhaul maintenance.

The number of breakdowns dropped to less than 1 per year and the amount spent on overhaul was also reduced. The pulverizer class achieved a total cost savings of $240,000 in the first year after these practices were implemented.

Measure the Cost of Proactive Maintenance. This category accumulates the actual costs for proactive maintenance measures. These actions are intended to extend machine life. Therefore, the expenditure occurs in different periods than the resulting savings. In fact, the actual savings from proactive maintenance measures become very difficult to track. Nonetheless, the expenditures are able to be categorized and historically tracked:

- cost of improved filtration,
- cost of root cause failure analysis, and
- cost of other root cause elimination.

Measure the Cost of Lube Procurement and Material Handling. This category typically accounts for 25% of the total tribology program cost savings. It involves accounting for the total investment procurement and handling of lubricants and hydraulics

- purchase fluids,
- store fluids,
- transfer fluid into machines using filter cart,
- remove fluid from machines,
- recycle fluids, and
- dispose of spent fluids.

Lubricant consolidation is an area that the condition monitoring team, assisted by consultation, can assist the procurement organization in achieving significant savings. Not only are savings available through improved purchasing power, there are less lubricants to inspect and inventory; and the problems associated with misapplication of lubricant are greatly reduced. In one case, a major steel manufacturer successfully consolidated 1400 different lubricant types to less than 100. This process was deliberate and took four years to achieve. It resulted in several million dollars savings per year.

Procurement of quality lubricants is an area that the plant condition monitoring team needs to be involved with. First, the purchase order needs to specify minimum lubricant condition properties and tests as needed to assure performance. These may include setting Target Cleanliness Levels (TCLs). However, a TCL requirement imposed on the supplier may cause the cost to be higher than filtering to acceptable TCLs at the plant. When purchasing large quantities of lubricant in bulk, it is advisable to require the supplier to deliver the shipment with a oil analysis report. Do not accept the shipment unless the driver arrives with this analysis in-hand. This is important because once the fluid is in the plant, it is too late do much about it.

Add to this the requirement to take two oil samples at the time the lubricant is filled into the plant reservoir. One of these goes back to the supplier, the other is sent to the plant fluid analysis laboratory.

Measure the Cost of Plant Power Usage. Contamination control and proper selection of lubricant viscosities can have an impact on plant power usage. This is another area in which consultation is required. One object here is to find the areas in which systems are operating with higher than required viscosity grades. High viscosity means high drag, increased power consumption, and increased fluid temperatures.

Since viscosity is strongly dependent on temperature, the condition monitoring team must identify the operating temperatures for high power machines. When the viscosity is above that required to support the lubrication regimes in the selected machinery, then reduce grades. At this point it is necessary to once again measure temperature since power loss is reduced due to viscosity.

Support and Implementation of Best Practices. It is advisable to take advantage of audits, start-up assistance, consultation, and training services which are available to support the plant tribology program.

Audit to Review Needs. Periodic auditing to review specific needs within the plant is suggested for best practice. CSI or other plants can be involved in this process. The CSI audit addresses all of the topics listed in this report. Each audit should compare this plant with plants identified as industry benchmark (e.g., those setting the highest standards for tribology practices). The audit report includes an assessment of performance and recommends activities for continuous improvement.

Continuous Improvement. After the initial audit, a continuous improvement plant is drafted. The plan includes objectives to be achieved during the following 24 months. Then quarterly reviews are conducted to measure progress. At each annual review, the plan is extended for another year. Each quarterly review is summarized in a status report to the maintenance manager and to the plant manager. The report includes available financial metrics (see section 3).

Network the Process. Communication is a valuable asset in successful program implementation. Effectiveness is improved by frequent exchange of tribology information. The condition monitoring maintenance team needs to be the central point of contact within the plant.

- between maintenance, production, and other departments (e-mail and periodic meetings),
- between different plant maintenance departments (e-mail and periodic meetings),
- with suppliers of on-site oil analysis equipment (phone and user group meeting),
- with tribology auditing, consulting, and training service suppliers (on-site quarterly audits plus scheduled training),
- with the fluid analysis laboratory (phone and electronic link via modem), and
- with suppliers of lubricants, hydraulic fluids, and filtration products (phone and on-site consultation).

Ensure the Process is Evergreen. The best way to ensure that tribology best practices remain "evergreen" is to document where the program started, where it is going, and what progress has

been made. Keep it visible. Keep it improving. The financial metrics (section 3) and the periodic audits (section 8) can help achieve both of these. People make success, not programs. Identify the people who are part of the tribology program effort. Train them, give them responsibility, and measure their progress. Most important, appoint a single person to be responsible for the total tribology program within the plant. Empower this person to build the program in accordance with management established objectives.

Conclusion. Tribology, which is the science of friction, lubrication and wear, is a fundamental to all mechanical systems. Production and profits can either benefit or be hurt by the approach that is taken to tribology. Industrial plants that are the benchmark performers in tribology for their industry take credit for large savings each year. These savings can result directly from oil analysis information as it reveals hidden information about machine wear condition, lubricant chemistry, or lubricant contamination. They can also result from effective lubricant procurement, storage, handling, and disposal practices, as well as root cause failure analysis, and resulting corrective measures. Probably the most important aspect of an effective tribology program is the way it is implemented by people. Do they understand tribology information? Do they know what to do with that information? Do they take ownership for the program and its results? Do they have management support? When the answers to these questions are all "yes," then the plant is on the way to benchmark status.

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THE MISAPPLICATION OF "COMPOSITE CORRELATION OF CLEANLINESS LEVELS"

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Abstract: Contamination control for hydraulics and lubricants is a proactive approach to achieve extended machine life. Particle counting is a proven contamination monitoring method and is an essential part of contamination control. Many particle counting standards have been developed and are in widespread use. Some include ISO 4406 code, particles per ml >10 micron, gravimetric method (mg/L), MIL STD 1246a, NAS 1638 code, and SAE code (Disavowed). The table, "Composite Correlation of Cleanliness Levels," has been used in many referenced publications to show equivalent relationships between all of these standards. In its correct application, this table shows the equivalence between these standards when using air cleaner fine test dust (ACFTD) standard contaminant. A frequent misapplication of this chart is to assume (incorrectly) that it describes equivalence when testing used hydraulic and lubricant oil samples instead of ACFTD standard contaminant. This paper shows the extent to which particle count data collected from actual samples does not comply with this table. It shows how one can be led to incorrect condition monitoring analysis and wrong recommended actions by using this table to translate "particles per ml > 10 microns" into ISO and NAS code levels. It shows the importance of actually counting particles at multiple sizes rather than assuming the size distribution of ACFTD standard contaminant.

Key Words: Particle count, flow decay, size distribution, filter blockage, cleanliness, Air Cleaner Fine Test Dust, ACFTD, ISO 4406, NAS 1638

Introduction: Table 1 , "Composite Correlation of Cleanliness Levels," or one very similar, has been printed in several publications.[1] This table shows a general comparison between several industry standard particle counting methodologies. This paper describes the error introduced using a single measurement to predict particle counts at various sizes. A study has been conducted of 3670 samples to determine how well one can estimate the ISO 4406 and NAS 1638 cleanliness codes based on particle counts measured in only one size range. For example this study shows that if one uses accurate > 10 micron data to

[1] Pg. 2 of SAE J1165 dated MAR 86, "Reporting Cleanliness Levels of Hydraulic Fluids"; pg. 203 of The Lubrication Engineers Manual, Second Edition, AISE dated 1996; pg. 78 of Fluid Contamination Control by E. C. Fitch, FES Inc. dated 1988; and page 283 of Handbook of Wear Debris Analysis and Particle Detection in Liquids by Trevor M. Hunt, dated 1993.

estimate particle counts and ISO codes at > 5 micron and >15 micron ranges, then only about half the results will report the correct code values and more than 10% of the results will be wrong by at least two ISO code values.[2]

Table 1. Composite Correlation of Cleanliness Levels

ISO Code	Particles/mL > 10 micron	ACFTD (mg/L)	MIL-STD-1246A	NAS 1638	Disavowed "SAE" Level
26/23	140000	1000			
25/23	85000		1000		
23/20	14000	100	700		
21/18	4500			12	
20/18	2400		500		
20/17	2300			11	
20/16	1400	10			
19/16	1200			10	
18/15	580			9	6
17/14	280		300	8	5
16/13	140	1		7	4
15/12	70			6	3
14/12	40		200		
14/11	35			5	2
13/10	14	0 1		4	1
12/9	9			3	"0"
11/8	5		100	2	
10/8	3				
10/7	2.3			1	
10/6	1.4	0.01			
9/6	1.2			"0"	
8/5	0.6				
7/5	0.3		50	"00"	

Particle counting is an accepted practice for monitoring fluid cleanliness affecting the life of hydraulics and lubricated machinery. Industry standards for particle counting (ISO 4406, NAS 1638, MIL-STD 1246C, SAE AS 4059B, DEF STAN 05-42/2, NAVAIR 01-1A-17, and others) all require particle counting to be accomplished at two or more relevant size ranges. All of these standards require measurements in the >5 micron and >15 micron ranges. All except ISO 4406 also require independent counts at >25 and >50 micron size ranges as well. When particle counts are measured at two different size ranges, one is able to measure both total contamination, and size distribution. Both are very important when monitoring fluid cleanliness.

[2] The ISO 4406 or NAS 1638 code values increase by one unit when particle count ranges double, and they increase by two units when particle count ranges quadruple. Since each code value in this study represents a large statistical population of data with approximately half the data in the top half of the range and approximately half the data in the bottom half of the range for that code value, it is reasonable to use the midpoint of the particle count range when comparing code values in this study.

Figures 1 through 6 illustrate the importance of particle size distribution for these industry standards.[3] Figure 1 shows how count distributions vary for ACFTD in concentrations ranging from 0.002 mg/L (lowest line) to 64 mg/L (highest line). . The dotted lines in Figures 1 through 6 represent 1 mg/L of ACFTD (same as one part per million using weight/volume units). Figures 2 and 3 show that for ISO 4406 a 3-code gap is parallel to ACFTD, while a 5-code gap traverses the distribution of ACFTD. Figure 4 shows how the NAS 1638 code also traverses the distribution of ACFTD. Figures 5 and 6 show how MIL STD 1246C distribution parallels ACFTD and how DEF STAN 05-42 Table B distribution traverses it. Size distribution must be measured for all of these standards.

Particle Counting by Light Extinction: "Light extinction" is an accepted method for all of the above standards when counting particles and measuring size distribution for hydraulic and lubricant samples. Light is extinguished (blocked) when they flow with the sample through an optical window. This sensor sizes every particle as it is counted, one-at-a-time. "Light extinction" sensors have three significant limitations: 1) false counts are logged when water droplets pass through the sensor, 2) false counts are logged when air bubbles pass through the sensor, and 3) the sensor becomes ineffective with extremely dark /opaque fluids or with sufficiently high particulate contamination levels to cause coincidence errors[4]. Procedures have been developed to compensate for each of these limitations including 1) masking water[5], 2) degassing samples, and 3) diluting samples.

Particle Counting by Flow Decay: "Flow decay" is an alternative method for estimating particle counts in single size category such as counts for particles > 10 micron size. Since it does not involve optical measurement, flow decay is not affected by water droplets, air bubbles, or dark fluids. This sensor detects the rate of blockage for a precision screen as particles larger than the screen pore size accumulate on the screen.

There are two common levels of flow decay contamination meter.[6] One level uses multiple screens (generally two or three with different pore sizes) so that size distribution can be effectively measured. The second level is simpler and requires less sample fluid because it uses only a single screen to trap contamination. It is this second level, the single screen type flow decay meter, that yields questionable ISO 4402 and NAS 1638 results since these standards demand measurement of size distribution.

The single screen flow decay meters measure the rate of change in flow when a screen, typically with 10 micron pore size, is being blocked with solid particles. A computer is used to translate this decay rate into actual particle count data which is reported in the >2

[3] Figures 1 through 6 provided by Trevor M. Hunt, Consulting Engineer.
[4] Coincidence errors occur when contamination levels are sufficiently high that two particles are likely to be in the light path at the same instant in time.
[5] A procedure has recently been developed accurately counting particles by light extinction with high water contamination. See "Masking Water in Mineral Oils When Using a Laser Particle Counter" by M. Lin, J. Mountain, and A. Carey, JOAP 98.
[6] The technique of flow decay used here is intended to reflect "filter blockage" as defined in British Standard 3406 Part 9 which describes two types: 1) a constant flow and measured pressure drop and 2) a constant upstream pressure and measured flow decay. Both types can have single or multiple screens.

micron, >5 micron, >15 micron, >25 microns, >50 micron, >100, as well as other micron size ranges. Implicit in this report is the assumption that all contaminants match a known size distribution such as that of the calibration standard, Air Cleaner Fine Test Dust (ACFTD). The only practical[7] way to make a single measurement with one mesh size and then report data at different sizes is to assume a consistent proportional relationship between these size ranges. This way if one knows the number of particles >10 micron size then all others are automatically known. Furthermore, this assumption must be made if one chooses to report ISO 4406 or NAS 1638 code values from a single flow decay measurement since these standards automatically include multiple size ranges

This assumption is NOT valid. Real world contaminants found in lubricants and hydraulics do not match the size distribution of ACFTD. Sometimes the distribution is flatter. Most of the time it is steeper. Steeper distributions are often found in systems with fine filtration. Flatter distributions are often found when contamination ingression or abnormal wear are occurring. The shape, or at least the slope, of the particle size distribution is just as important as the overall level of contamination.

Note also that the introduction to ISO 4406:1987 includes: "Most methods of defining solid contaminant quantities are based on the supposition that all contaminants have similar particle size distribution. This supposition may be valid for natural contaminants, such as airborne dust, but it is not valid for particles which have been circulated in an installation and subjected to crushing in pumps and separation in filters." Note also that ISO 3939:1986 includes: "The assumption is made that particle count distribution curves approximate straight line segments when plotted on log/log-squared graph paper. The assumption of straight line distribution (when plotting particle count data on log/log-squared co-ordinates) may not always be valid."

A single measurement for >10 micron size can only predict the counts at other sizes if the contaminant is a standard such as the particle counting calibration standard, ACFTD. When one measures the contamination level at one size with ACFTD, all other sizes are automatically known[8] and increase or decrease in proportion to the mg/L of ACFTD. This was a critical factor in selection of ACFTD as the calibration standard for nearly all particle counters manufactured for the purpose of measuring particulate contamination in either lubricants or hydraulics.[9]

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[7] The logarithmic decay of particle counts with size creates a practical limitation for quantifying size distribution with flow decay through a single mesh. In effect, the numerically dominant contributor to mesh plugging (flow decay) is the group of particles which are a little larger than the mesh opening size. The very large particles are too few in number and the very small particles pass through the mesh. However, R. Lewis gave some evidence that the rate of change in pressure decay might be "related to the different particle size distributions" shown in Figures 4 through 7 of his paper, "An integrated Oil Analyzer," pg. 412-422, Condition Monitoring 94. In this paper Lewis concluded that small particles cause increasing flow decay as they fill interstitial spaces between larger particles.

[8] The "known" size distribution for ACFTD is under revision by standards committees responding to new data from the National Institute for Standards and Test (NIST). Revisions, when published will affect all particle counting methods and standards in a similar way. Data reported in this study assumes the historical ACFTD counts at > 5 and > 15 microns. It is now understood that these counts actually apply to > 6 and > 14 microns.

[9] Note that latex spheres and other materials may be used when calibrating particle counters for other purposes.

A Study Comparing ACFTD Size Distribution to More Than 3000 Actual Oil Samples. A study of particle count data from 3670 different samples[10] was performed to investigate the similarity of ACFTD size distribution to that found in "real world" used lubricant and hydraulic oil samples. The study was done to investigate the likelihood of error resulting from estimating ISO 4406 codes for both 5 ("ISO5") and 15 ("ISO15) micron sizes and estimating the NAS 1638 code using only the true particle count at 10 micron size and the assumption that the size distribution matched that of ACFTD. The results were surprising.

ISO 5 micron code: The study showed that the ISO5 code was correct approximately 45% of the time when using accurately measured counts at >10 micron size to estimate counts in the >5 micron size range, and assuming the log/log squared distribution to be the same as ACFTD. See Figure 7. In fact, 10.5% of the measurements (10.5 = 3.3 + 5.7 + 1.3 + 0.2) are in error by 2 or more ISO5 code levels. This implies that the average estimated particle counts > 5 microns can be either understated by more than 75% or overstated by more than 400%.

ISO 15 micron code: This study also indicated that the ISO15 code was correct approximately 39% of the time when using accurately measured counts at >10 micron size to estimate counts in the >15 micron size range, and assuming the log/log squared distribution to be the same as ACFTD. See Figure 8. In this case, 14.6% of the measurements (14.6 = 0.1 + 0.1 + 10.8 + 3.6) are in error by 2 or more ISO 4406 code levels. This implies that the average estimated particle counts > 15 microns can be either understated by more than 75% or overstated by more than 400%.

Variations in Sample-to-Sample Size Distributions: The reason why the >10 micron particle count cannot be reliably used to estimate the counts at neighboring sizes, >5 and >15 micron is simply a matter of variation in actual size distributions. To explore this, 24 typical oil samples were selected including hydraulics, gearboxes, compressors, and other industrial machinery. Table 2 shows that for ACFTD the >5 micron count is always 359% (3.59 times) of the >10 micron count, and the >15 micron count is always 38% of the >10 micron count. However, in a sampling of 24 actual oil samples, the >5 micron count averaged 1449% of the 10 micron count (instead of 359% for ACFTD) and the >15 micron count averaged 25% of the 10 micron count (instead of 38% for ACFTD). The range of proportional differences between >5 and >10 micron counts in actual data varied from 295% to 13,242%, a factor of 44 times or 6 ISO 4406 code levels. The range of proportional differences between >15 and >10 micron counts in actual data varied from 3% to 44%, a factor of 14 times or 4 ISO 4406 code levels. Although ACFTD is in the ranges for both sizes, neither ACFTD nor any other standard contaminant, could be selected to represent the variations observed in real world samples.

[10] These samples represent a consecutive block of data collected by the CSI Trivector oil analysis lab.

Table 2. Size distribution variations between ACFTD and "real world" samples.

	ACFTD	24 Typical Oil Samples		
		max.	min.	ave.
100% * (count @ 5) / (count @ 10)	359%	13,242%	295%	1449%
100% * (count @ 15) / (count @ 10)	38%	44%	3%	25%

If the >10 micron particle count cannot be reliably used to estimate the counts at neighboring sizes, it follows that it is meaningless to use it to estimate counts at other sizes such as >2, >25, >50, and >100 micron. This is exactly what must be done if one is to apply this approach to industry standard codes such as NAS 1638 which require independent counts for each range: 5 to 15 micron, 15 to 25 micron, 25 to 50 micron, 50 to 100 micron, and >100 micron.

NAS 1638 code: This study of 3670 samples showed that the NAS 1638 code was correct approximately 51% of the time when using accurately measured counts at >10 micron size to estimate counts in specified size ranges, and assuming the log/log squared distribution to be the same as ACFTD. See Figure 9. In this case, 12.2% of the measurements (12.2 = 3.9+ 7.2 + 0.4 + 0.7) are in error by 2 or more NAS 1638 code levels

ISO and NAS codes: Figure 10 shows the error plots for ISO 4406 at both >5 and >15 microns, as well as NAS 1638 cleanliness codes if one were to extrapolate from a single >10 micron flow decay type measurement. It is important to note that one finds valuable information in the "tails" of these distributions. For instance, a few particles per ml > 50 micron will trigger the NAS 1638 Code without affecting the ISO 4406 alarms. This approach can give early indication of wear problems, filtration problems, and contamination problems that may otherwise have gone unnoticed..

Actual Distributions Do Not Follow ACFTD: Figures 11 and 12 show actual data from typical oil samples (4 hydraulic, 4 compressor, 4 gearboxes, 3 spindles, and 5 crank ends) plotted on a background of ACFTD data (dotted lines). This graph clearly shows that some of the time the actual distribution is flatter than the ACFTD although most of the time it is steeper. The spacing between dotted ACFTD lines in this plot is two (2) ISO 4406 or NAS 1638 codes or 400% count difference per space. The lowest dotted line is ISO 6/3 due to 0.001 mg/L[11] of ACFTD, and the highest dotted line is 26/23 due to 1,024 mg/L of ACFTD. It is interesting to note that the target cleanliness level for vane pumps, piston pumps, or motors of 16/13[12] per ISO 4406 or 11 per NAS 1638. This corresponds to only 1.0 mg/L, or about 1 ppm ACFTD!

[11] Note that "mg/L" units are commonly used for particulate contamination and represent parts per million (ppm) with mixed units of weight per unit volume.

[12] Page 14 from "The Handbook of Hydraulic Filtration" by Parker Filtration

Conclusion: The primary conclusion of this report is that at least two measurements at differing size ranges must be made in order to make reasonable conclusions about particle size distribution. While ACFTD, which is an excellent calibration standard, may be sufficient to represent wind blown dust; it does NOT represent the size distribution for contamination found in typical industrial machines. It appears that contamination in industrial machinery lubricants and hydraulics can have size distributions with slopes differing by hundreds, even thousands, of percent. The often cited table, "Composite Correlation of Cleanliness Levels," is useful as a qualitative comparison between various industry standards assuming the contaminant measured is ACFTD. However, since this table gives no allowance for variations in size distributions, it may not be appropriate to use it for cross referencing actual sample data.

Figure 1. ACFTD Standard Contaminant

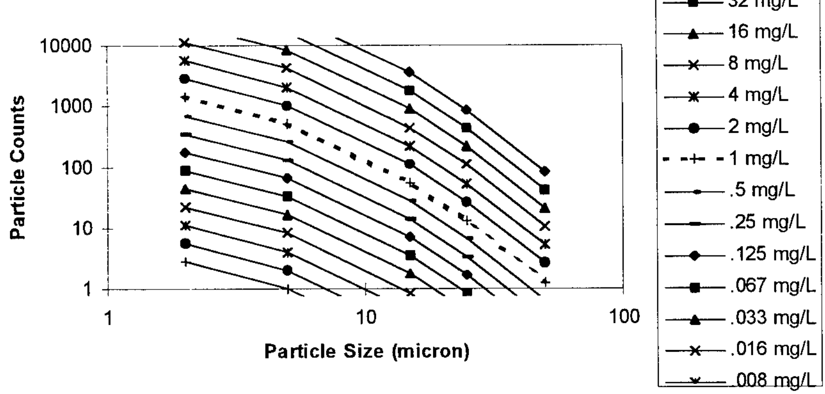


Figure 2. ISO 4406 w/ 3 Code Gap

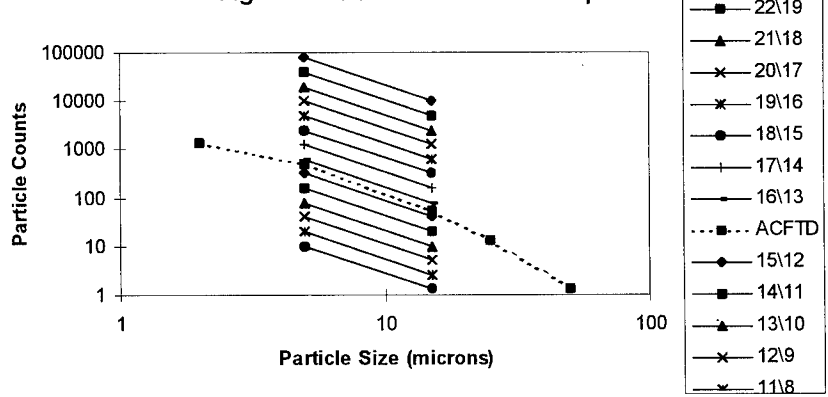


Figure 3. ISO 4406 w/ 5 Code Gap

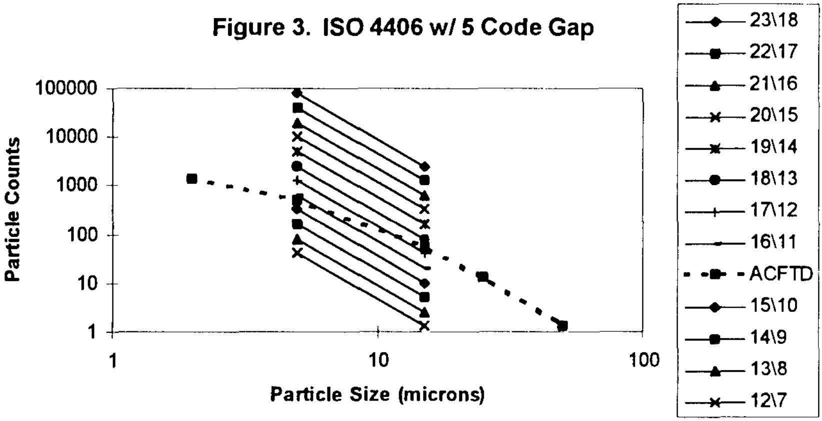


Figure 4. NAS 1638

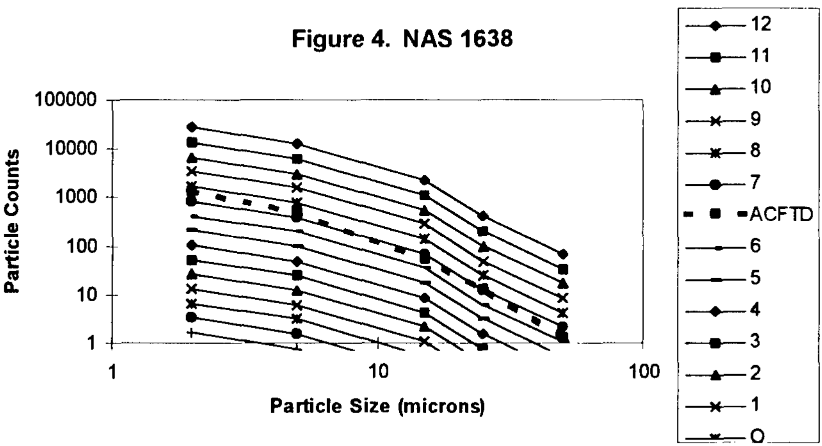


Figure 5. MIL STD 1246C

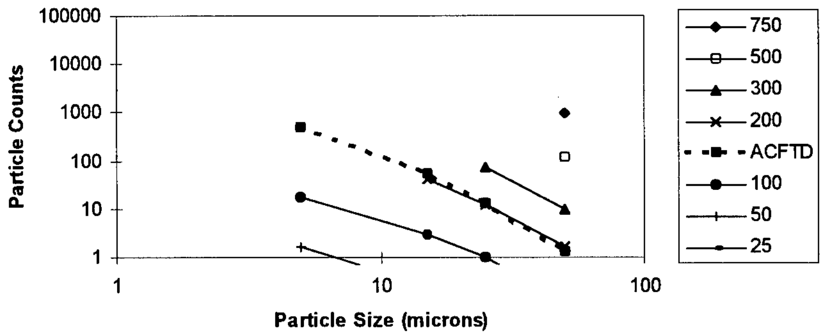
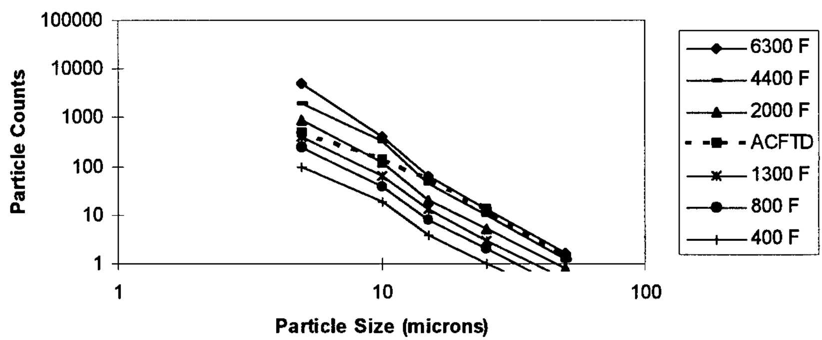


Figure 6. DEF STAN 05-42 Table B



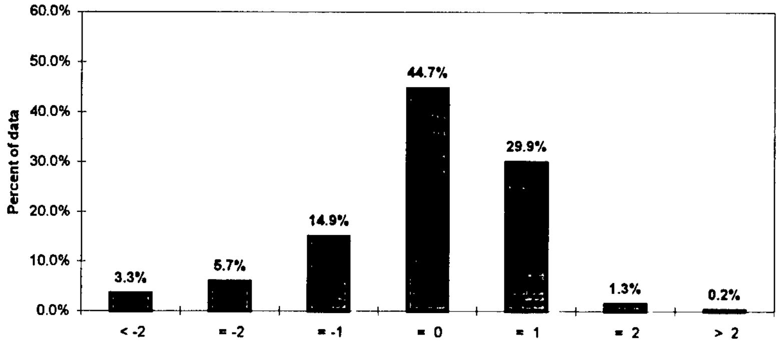


Figure 7. Estimated ISO 5 - Measured ISO 5 Code for 3670 Samples
Estimated ISO 5 Code is extrapolated from measured 10 micron count using slope of ACFTD

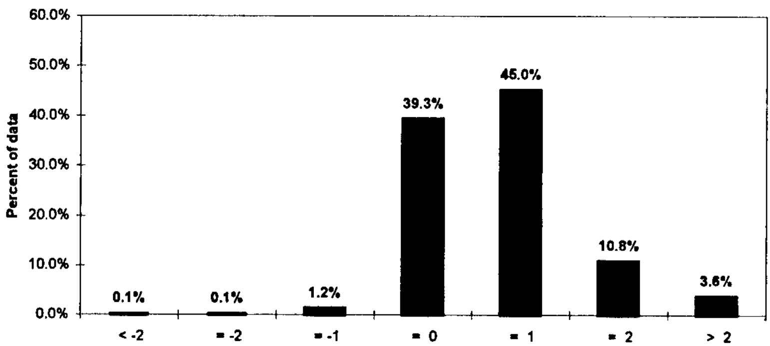


Figure 8. Estimated ISO 15 - Measured ISO 15 Code for 3670 Samples
Estimated ISO 15 Code is extrapolated from measured 10 micron count using slope of ACFTD

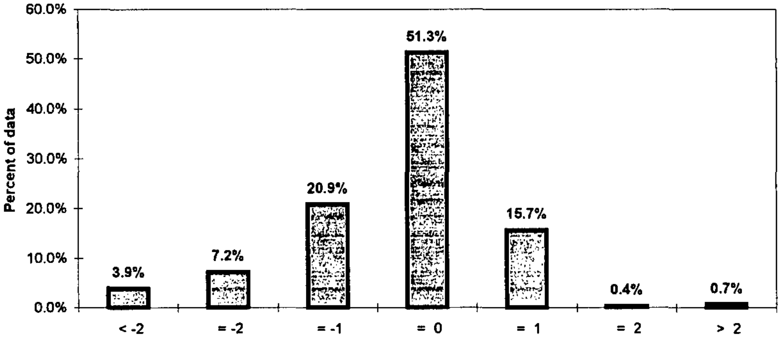


Figure 9. Estimated NAS - Measured NAS Code for 3670 Samples
Estimated NAS Code is extrapolated from measured 10 micron count using slope of ACFTD

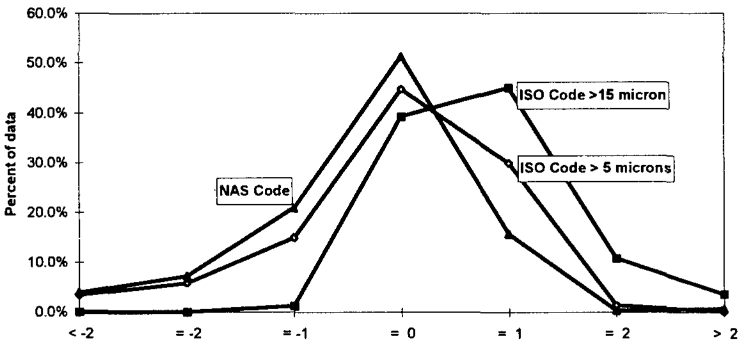


Figure 10. Estimated Code - Measured Code for 3670 Samples
Estimated Code is extrapolated from measured 10 micron count using slope of ACFTD

Figure 11. Comparison typical sample size distributions (solid lines) with ACFTD size distributions (dotted lines)

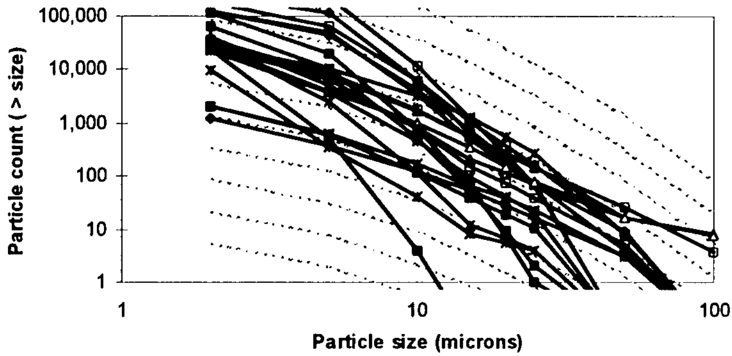
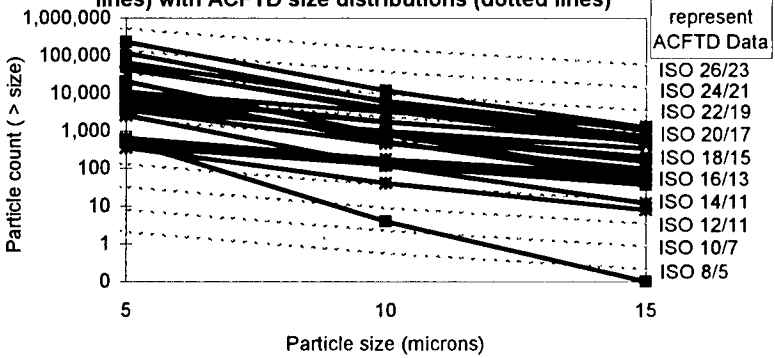


Figure 12. Comparison typical sample size distributions (solid lines) with ACFTD size distributions (dotted lines)



Fuel Soot Monitoring by Light Extinction Measurement (LEM®)

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Abstract: Fuel soot is the primary contaminant in diesel engine lubricants. Evolving emission regulations, engine designs and oil formulations are all centered around the control and retention of soot particles and advanced gel formations. Accurate, reliable and cost effective measurement of soot is now an essential requirement for an effective oil analysis program.

Key Words: Agglomerations; Dispersant additives; Fuel soot; Interferences; Light Extinction Measurement (LEM); Thermogravimetric Analysis (TGA).

Introduction: Fuel soot is formed during the normal combustion processes in diesel engines. These soot particles will vary in size and shape. The rate at which soot is generated is also variable and dependant upon many factors. The factors that affect the creation of soot can include:

- Engine type, size and configurations.
- Equipment applications, operating modes and frequencies.
- Fuel delivery and control settings.
- Intake, exhaust and EGR conditions.
- Wear modes of the engine and fuel delivery components.
- Equipment age.

During engine operations, soot particles are either emitted within the exhaust, retained in the combustion chamber, or transferred into the engine's lube oil via blow-by and wash-down within the oil film on the cylinder/liner surfaces (thermophoresis). Soot particles and formations comprise the largest volume of contamination present in used diesel engine oils.

Regardless of disposition, soot is an undesirable element that creates problems for equipment owners, operators and maintenance personnel:

1. Exhausted soot is an environmental pollutant.
2. Soot retained in combustion areas contributes to deposit formations.
3. Soot that enters the crankcase depletes oil additives, forms gels that thicken the oil and evolves into hard deposits that promote wear!

Internal control of these soot formations is accomplished by dispersant lube oil additives. These dispersants are charged with preventing gel formation, conveying larger formations to the filter for removal, and retaining the smaller unfiltered particles in suspension.

Discussion: In addition to problems and influences fuel soot has presented in the past, we are now contending with even greater soot levels. The U.S. Federal Heavy-Duty Diesel Emission Standards, as well as state and local regulations, have included stronger controls of engine exhaust emissions.

To meet these new standards, one area of major change in equipment designs have been through increased usage of exhaust gas recirculation (EGR) systems. Recirculating systems will decrease emissions. However, they also increase the soot levels deposited into the lube oils (estimated at typically +15%) increasing the demand upon dispersant additives and diminishing the performance and safe life of lube oils.

These changes have also placed greater demand upon oil testing programs to provide accurate and reliable information for safely controlling oil and filter service intervals. Lube oil testing programs include many different tests in attempts to segregate and measure representations of soot in the lube oil. However, soot is an evolving compound of carbon and hydrogen that has varying structures which are present in more than one form or "stage". Coupling this with the reactions and combined effects of other oil properties and conditions creates major limitations in accurately measuring soot levels.

Standard tests available for measuring soot levels have not been capable of segregating and accurately detecting the actual minute soot particles. Most methods rely on the use of a dilution agent (solvent) to "release" suspended soot from within an oil and then centrifuging the sample to determine the level of soot present (represented mass).

Based on the assumption that the majority of particulate being removed is soot, these methods were effective for the given times, products and purposes. However, due to greatly improved dispersant used in today's engine lube oils, the agents used in these testing procedures can no longer remove all of the particulate for accurate and reliable measurements!

Test Methods: A summary of the test methods most commonly used in oil analysis programs is as follows:

•**Total Solids:** There are many variations of this test used to obtain a representation of the "total solids" present in lube oil. Typically, a sample is diluted with a solvent, centrifuged to remove any particulate, and the result is applied as a representation of soot levels. These tests cannot segregate and measure soot alone. They can only express a representation of the *total contaminants* that are: (1) Not suspended within the oil and (2) That can be released or "stripped" from the dispersant additives.

The obvious limitation is that the extracted "solids" can also include: Oxidized oil products, sand or dirt, wear metals, gasket, seal or hose materials, filter media or fibers, paint chips, water and any other solid foreign materials that may enter the engine.

However, the <u>major limitation</u> of these tests lies within the current generation of engine oils; Many dispersant additives are so effective, the soot particles and formations cannot be adequately released, extracted and measured.

• **Soot (Abs) by Infrared:** Infrared (FT-IR) analysis [1] is the most common test performed for expressing a specific "Fuel Soot" level and has been used within the lube testing industry for many years. The main criterion for using infrared is the low cost of performing the analysis and several other properties and contaminants can be measured within the same procedure.

Infrared does not measure any organic presence relative to soot. Infrared operates through the function of light transmission through a fluid sample and the assumption is that only soot particles will absorb or block out the infrared light [1,2].

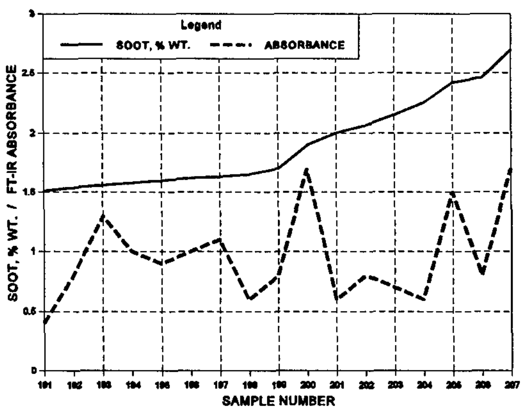

Figure I. Examples of light scattering affects upon samples with soot greater than 1.5% wt.

Soot particles are actually "black carbon" and high concentrations can totally "block out" the infrared light transmission, limiting the detection range. Since soot is basically carbon, wear metals and oxidation products in the oil can become adsorbed onto soot particles. Also, the presence of gels within soot formations can distort the light transmission, resulting in "light scattering" [3]. These interferences greatly affect both accuracy and repeatability.

There are many types of IR instruments that operate on similar principles. However, these

instruments do not always produce equal or comparable results. Nor are there any common "soot standards" available for calibration and/or standardization. Results are typically reported in units of absorbance (ABS) which are not converted or related to an actual percent of mass or volume [1,2,3].

Our research has shown that IR can be a relatively acceptable indicator, providing the soot is present in "normal to moderate" (<1.5%) levels. When higher levels of soot that are important to the evaluation of the engine and lube oil are present, the implied soot levels by infrared detection (ABS) *can actually decrease* due to the presence of gels and agglomerated soot masses.

• **Pentane Insolubles:** When properly performed by ASTM D893 [4], pentane insolubles (PI) are applied as a representation of agglomerated soot (masses) for an indicator of the oil's dispersant (additive) efficiency. The complexity of this procedure prohibits it's use and application in a production laboratory environment.

This test is more accurate and reliable than a "total solids" test but does not measure, nor account for, the total (dispersed) soot particles present. This method actually measures the affects of already failed or "tied up" dispersant. At this point gels, sludge and deposits may have already formed within the engine.

• **Thermogravimetric Analysis (TGA):** TGA represents the weight change of a material as a function of temperature during thermal processing. As performed on used diesel engine oil, TGA measures the carbon present within the sample. Since soot is basically carbon (though not completely), TGA has been the most accurate representation of soot available for many years. Both the complexity and costs of this procedure prohibits it's use and application in a production laboratory environment.

Even TGA has limitations; TGA results can be affected by the presence of hydrocarbons. Carbon is a major ingredient in both diesel fuels and crankcase oils. Most diesel engine oils also contain calcium carbonate (additives) which can affect the test results [3]. Good reference oil's are required for TGA analyses.

Analysts' Commitment: Analysts, Inc. has been an innovating leader in lube oil analysis for over 37 years. We have always been aware of the value and importance of accurate soot detection and monitoring for diesel engines. We have utilized all of the fore-mentioned testing procedures in our efforts to provide the best services possible. Time has reflected many changes:

1. Lube oil additives have surpassed the ability of simple extraction tests being able to remove the soot for measurement. The levels of soot being inducted and retained within the oils have surpassed the abilities of IR to be an applicable indicator.

2. The cost of lube oils, as well as storage, handling and disposal has increased considerably.

Maximum safe utilization of our oil is "a must" for profitable equipment operation.

3. Engine manufacturers are being required to modify equipment and develop new designs that reduce emissions. These changes are not just reflected in increased costs for new equipment, but the costs of routine operations, maintenance, repair and replacements have also escalated.

Just as insufficient services can be costly in engine wear and component repair or replacements, premature services can also be very costly. A major contributor toward control of these costs is an accurate and affordable means of monitoring soot levels to determine whether the oil is adequately dispersing the soot particles and at what point are the oil's additives being "loaded" and require replacement.

Important as this information has always been, it is even more crucial for the engines of today and tomorrow. With this in mind, Analysts, Inc. charged it's Research and Development Group with the challenge of developing a means of *specifically measuring dispersed soot* in diesel engine oils. The requirements included:

1. Accuracy that was free of the interferences of present methods.
2. Measurement without the need of specific reference oils.
3. Dynamic range of detection.
4. Repeatability.
5. Cost effective production for routine oil analysis programs.

Light Extinction Measurement (LEM): In 1993 Analysts' Research and Development Group, under the direction of Dr. William Seifert and Vernon Westcott (founding developers of Ferrographic Analysis), succeeded in our quest to provide a reliable and affordable means of detection and measurement of dispersed soot within used diesel engine oils.

The instrument developed utilizes the methodology of Light Extinction Measurement [3], hence the name LEM®. The method qualifies in all the fore mentioned requirements and has proven to be so revolutionary, it provides data that has never before been so readily available!

LEM detection [3] is the extension coefficient of the fluid to the passage of broad band light. White light is used to avoid molecular resonances of compounds. Dispersed soot particles are measured in ranges from a few nanometers in diameter to typically 200 nanometers. Should a degree of resonances appear, the broad band (white light) eliminates any significant error.

The detection and measurement of the actual soot particles (spheres) is accomplished "directly within the sample"[3]. LEM does not rely upon solvent dilutions to release the particulate, separation of "solids" by a centrifuge, flame or heat to consume the sample, nor transmission of an infrared light through the sample.

The later point is extremely important. The "soot load" of many oils is too high to allow passage of an infrared light transmission. As soot gels and forms agglomerations, infrared transmission is further "blocked" by the total of the formed masses. LEM detects the actual dispersed soot particles and the broad band white light is not deterred by the presence of gel within the formations. Where extreme levels of soot are present and/or the soot has been allowed to agglomerate due to depleted dispersant, the introduction of fresh dispersant additives provides the means for unlimited measurement capabilities (Based on the principle of Lambert-Beers Law [5]).

The measurements are relative to the mass and reported in percentages (% mass) that can be reliably applied to OEM recommended guidelines for maximum allowable soot as determined by TGA.

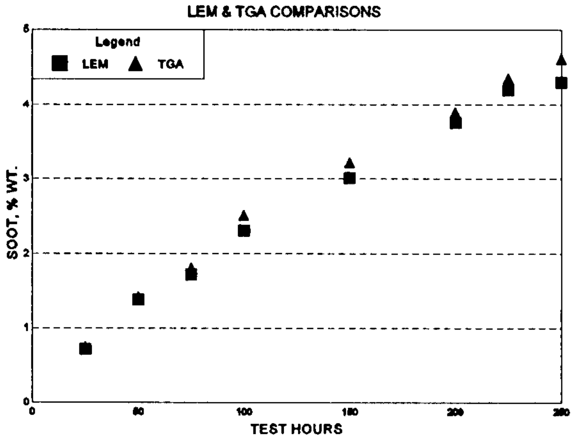

Figure II. Comparison of LEM and TGA data through a MACK T-8 engine soot test.

Confirmations: The development of LEM was accomplished with the cooperation and assistance of several lubricant, additive and engine manufacturers. LEM instrumentation was installed on-site within Chevron Research (CRTC) and Detroit Diesel's Central Chemical Laboratory. Other participants included Pennzoil Research, Lubrizol Corporation and Mack Engineering.

During the initial installation at DDC, the LEM was stringently compared to results obtained from their own TGA lab[6]. The regression output of LEM to TGA was $R^2 = 0.998$! This is quite remarkable, especially where two different methodologies are employed. In such studies, a factor of $R^2 = 0.80$ can be considered sound and acceptable.

Additional accuracy and repeatability studies were performed within the DDC Central Laboratory and in 1994 the report at the conclusion of their research stated "The data generated qualifies LEM (Light Extinction Measurement) to be used as an alternative to TGA [6] for measurement of soot in used engine oils....". Their report further stated "The other key factor" related to the productivity of LEM which within their own lab was "evaluated as LEM:TGA::8:1."

Pennzoil's Research Laboratory compared Analysts' application of LEM results toward dispersant additive effectiveness and depletion. The results obtained within their lab confirmed the accuracy and dependability of our interpretations.

In 1995 Mack Engineering Group [7] re-established their soot limitations within Mack engines. The new guideline of acceptability to 4.0% specifies "determination by LEM."

Conclusion:

Analysts' Light Extinction Measurement (LEM) for diesel fuel soot analysis is at minimum, equal to the most accurate means available (TGA) to date. LEM requires no special reference oils or standards to perform the analyses. The production capabilities of LEM allows Analysts, Inc. to provide precise data and interpretations to clients without timely delays or exorbitant cost.

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Proactive and Predictive Strategies for Setting Oil Analysis Alarms and Limits

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Abstract: In oil analysis, well placed alarms and limits are like trip wires, alerting operators and technicians to an untoward or threatening condition. Oil analysis limits can vary considerably according to machine type, oil type, and reliability goals. This paper discusses four distinct types of limits and how they are applied to different machine and lubricant applications: goal-based limits, aging limits, rate-of-change limits, and statistical limits.

Keywords: Alarms; proactive; predictive; condition-based oil changes; limits; rate of change limits; contamination.

In the past, users of oil analysis have relied almost exclusively on the commercial laboratory to set and enunciate data alarms. This has put an unrealistic burden on the labs to understand information about user-equipment they have never seen. Likewise, the goals and objectives of the user with respect to reliability and maintenance may not be fully understood. Usually, this leaves the lab with no alternative other than to use standard default alarms. When these one-size-fits-all alarms are used, many of the opportunities and objectives of a modern condition-based maintenance program are missed.

In recent years, with the advent of sophisticated user-level oil analysis software, many site oil analysis technologists are taking responsibility for setting alarms and limits independent of the lab. The lab, in turn, is being asked to only deliver accurate and timely oil analysis results, leaving interpretation and exception reporting to the user. With the user being familiar with the lubricants, machines, historical problems, and general reliability goals, the most proper and effective limits can then be set. However, a critical ingredient is a sufficient level of training in oil analysis by the user.

What are Oil Analysis Alarms and Limits?: When plant-level oil analysis software is employed, one of the main benefits is the funneling down (or filtering) of the amount of data actually viewed and analyzed. This data reduction goal is essential and relates to the tactical goal of exception reporting, that is, the viewing of only the data that is out of compliance with acceptable trends or levels. All other data is held and managed in a database for future reference and use. The limits, when properly set, give confidence that conforming fluids are, in fact, okay and that non-conforming conditions have been caught proactively.

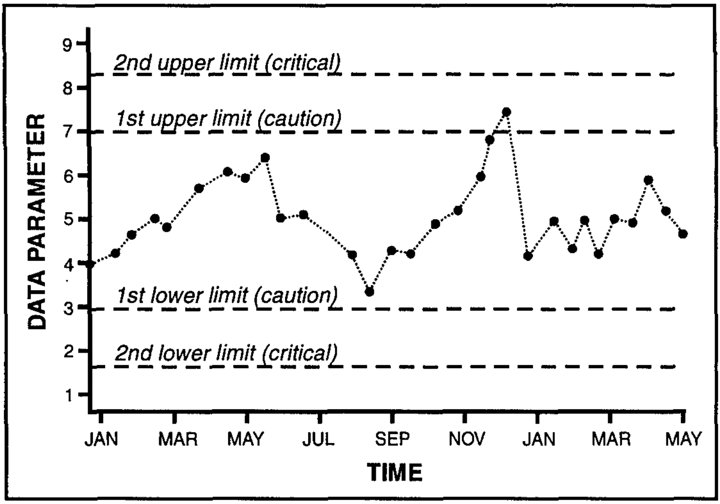


Figure 1
Illustration of Upper and Lower Oil Analysis Limits

Because the goals and expectations vary considerably from one organization to another these limits are best set by those charged with the responsibility of machine reliability and long fluid life. They are also influenced by machine and application specific considerations. For instance, where the gear box loads and duty cycle are low in one application, they may exceed rated levels in another. The availability of spares and standby equipment may influence the decision with equal magnitude. And, the age of the machine or lubricant may impact the placement of limits in certain cases.

Basically, a limit or alarm is a strategically placed "trip wire" that alerts you to an abnormal condition. Some data parameters have only upper limits such as particle counts or wear debris levels. A few data parameters apply a few lower limits like TBN, additive elements, flash point, and FTIR (additive). Other data parameters use both upper and lower limits. These might relate to important chemical and physical properties of the lubricant such its viscosity (see Figure 1). The computer trends the data and normally no alarm is reported as long as the limits are not exceeded. When an exception exists the

software is designed to alert and direct corrective action in response to the deleterious result. To insure maximum benefit from oil analysis, careful thought needs to go into the type of limit used and its setting.

Some Limits are More Proactive: Proactive limits are designed to alert users to abnormal machine conditions associated with root causes of machine and lubricant degradation. They are keyed to the proactive maintenance philosophy of setting targets (or standards) and managing the lubricant conditions to within the targets. A strategic premise is that these conditions are controlled to levels that are improvements over past levels and that these become goals. Best results occur when progress towards achieving these goals are charted conspicuously by the maintenance organization. These types of limits are referred to as "goal-based," see Figure 2.

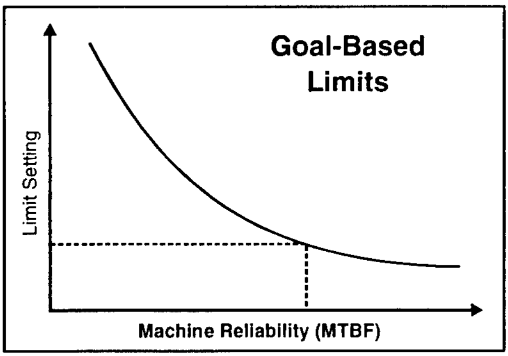


Figure 2
Goal-Based Limits Are Set For Certain Data Parameters To Proactively Improve Machine And Lubricant Reliability

In order to set a goal-based limit a level of machine reliability is identified. Again, this needs to be an improvement over previous levels. If, for instance, we use particle count as the parameter then we need to select a "target cleanliness" which is a marked improvement from before. The target cleanliness becomes the limit. In the example, if previously contaminant levels were averaging about ISO 18/15 for a hydraulic system, a limit set at 15/12 would be a goal-based improvement. A life extension of three times (MTBF) would be expected based on controlled field studies. If, on the other hand, we set a limit of 18/15 our effort is downgraded to the detection of major faults only. Goal-based limits of this type can be applied to particle counts, moisture levels, glycol levels, fuel dilution, TAN, and other common failure root cause conditions.

Another similar type of proactive limit relates to the progressive aging of the lubricant or hydraulic fluid. From the moment the oil is first put into service its physical and chemical properties transition away from the ideal (i.e., those of the new formulated oil).

For some properties the transition may be extremely slow but for others it can be abrupt and dynamic. Limits keyed to the symptoms of lubricant deterioration are referred to as "aging limits," see Figure 3. They are designed to signal the need for a well-timed condition-based oil change and are usually pegged to the depletion of additives and the thermal/oxidative degradation of the base oil.

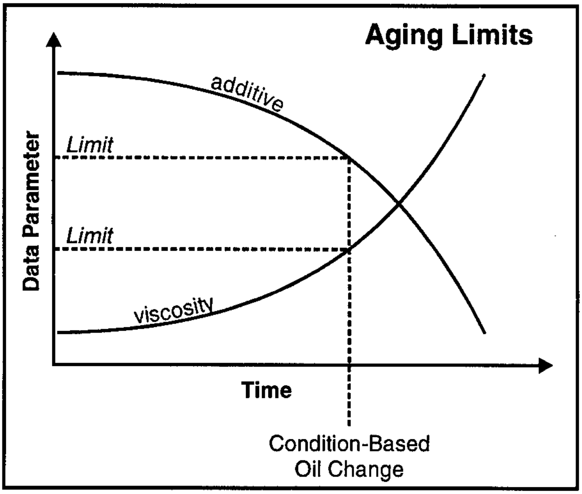


Figure 3
Aging-Limits Are Keyed To Degrading Additive And Base-Stock Properties

In order to properly set aging limits the new lubricant must be analyzed to reveal its physical and chemical properties. This will become the oil's "base signature." Care must be taken to insure that the new oil is analyzed using the same test procedures and instruments that will be used to analyze the used oil. Under no circumstances should these "base signature" properties be simply lifted off the lubricant's spec sheet as provided by the supplier. Instruments and test methods vary substantially and new oils are approved if their properties fall within a tolerance range.

For instance, ISO viscosity grades vary plus/minus ten percent from a nominal center point (grade). This means that a VG 68 lubricant would be "in grade" from 61 to 75 centistokes (cSt). This is too much variance for 68 centistokes to serve as a proper baseline. However, if the actual viscosity of a specific lubricant was measured and found to be 64 cSt then a precise baseline is now available against which the used oil can be trended. Aging limits can be effectively applied to such parameters as TAN, TBN, viscosity, RBOT, emission spectroscopy for additive elements, FTIR (for oxidation, nitration, & sulphation), and dielectric constant.

Aging limits often follow trendable data patterns, i.e., they trend steadily in the direction of the limit. The actual time to limit might be predicted by linear or non-linear regression; a feature in some oil analysis software products. For instance, the following equation might be applied to estimate the remaining useful life of a turbine oil using Rotating Bomb Oxidation Test (RBOT):

$$\text{Percent remaining oxidative life of oil} = \frac{\text{RBOT used oil}}{\text{RBOT new oil}} \times 100$$

Lower aging limits are generally set for additive depletion, RBOT life, and TBN. Upper limits are set for dielectric constant, TAN, and FTIR for oxidation, sulphation, and nitration trends. And both upper and lower limits should be set for viscosity. The table in Figure 4 shows some example limits for both goal-based and aging parameters.

Goal-Based Limits (upper)			**Aging Limits**		
	Caution	Critical		Caution	Critical
Cleanliness	14/11	16/13	Viscosity	+5%	+10%
Dryness	200	600	RBOT	-30%	-60%
TAN	0.2	0.4	FTIR-Ox	0.3	1.0
Fuel	1.5%	5%	Zinc	-15%	-30%
Glycol	200 ppm	400 ppm	Calcium	-10%	-20%
Soot	2%	5%	TBN	-50%	-75%

Figure 4
Example Goal-Based and Aging Limits

Other Limits are More Predictive: Predictive limits are set to signal the presence of machine faults or abnormal wear conditions. They are aligned with the goals of predictive maintenance, i.e., the early detection of machine failure symptoms as opposed to failure root causes (proactive maintenance). In oil analysis, a proper predictive limit set to the correct parameter has many advantages over other predictive maintenance technologies. Specifically, it offers reliable incipient fault detection, spanning a wide range of machine failure modes. It is seer-like in that it has the ability to forecast a future event. As compared to vibration analysis for instance, the time-based detection window using ferrous density analysis has been demonstrated to exceed 15 times for common gear boxes failures.

Rate-of-change limits are generally identified as predictive. These are set to a property that is being progressively introduced to the oil, such as wear debris. The add rate (change) might be calculated per unit time, for instance ppm iron per 100 hours on oil. When the parameter's value is plotting against time the rate-of-change (add rate) equates to the current slope of the curve. As an alternative to representing rate-of-change, slope can be quantified by dividing rise by run for a fixed period of time (see Figure 5). The

linear trends also points to the approximate time interval remaining before a level-type limit is exceeded. Unlike level limits however, rate-of-change limits ignore the absolute value of a data parameter, emphasizing instead the speed (rate) at which the level is changing.

This can be best illustrated by an example. Suppose for a given machine, such as an industrial gear unit, iron is typically introduced to the oil at roughly 5 ppm per month. The first month after an oil change the iron shows 5 ppm, the expected level. After the second month the iron shows 10 ppm, again this is expected (5 + 5). The same holds for the end of the third month when 15 ppm is reported. The add rate of 5 ppm per month remains uninterrupted. However, by the end of the fourth month the unexpected result of 50 ppm is obtained. The computer software shows this as a critical. The reason is not due to the fact that 50 ppm in a gear lube signals abnormal wear. In fact this is a rather common iron concentration in gear oils. However, the alarm is responding to the rate at which the iron concentration changed in the last month of service (35 ppm instead of the expected 5 ppm). Had rate-of-change limits not been applied this exception might not have been reported.

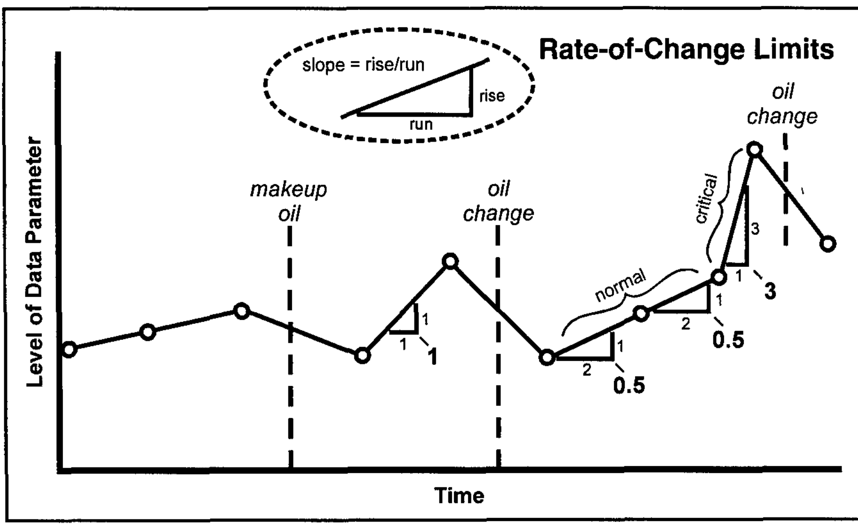
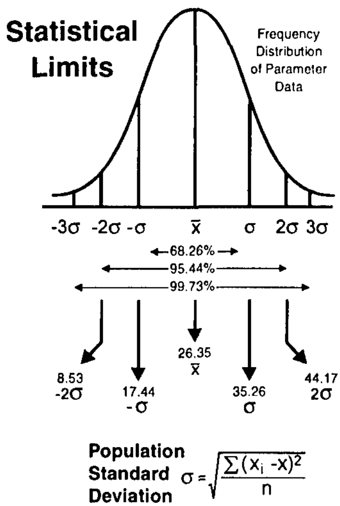


Figure 5
Using Rate-Of-Change Limits (rise/run) Must Be Calculated For The Trending Data Parameter

The use of rate-of-change limits is well suited for wear debris analysis but can be used for other parameters as well. Examples of where it is commonly applied include particle

counts, elemental wear metals, ferrous density analysis (DR, PQ 90, Wear Particle Analyzer, ferrous Contam-Alert), TAN, and RBOT. It should be noted that multiple limit strategies can be used for single test parameters, i.e., where rate-of-change limits are applied so too are level limits (aging, proactive, and statistical).

Statistical Limits are Predictive as Well: For many years statistical limits have been used successfully in oil analysis. The practice requires the availability of a certain amount of historical data on the target parameters (see Figure 6). A population standard deviation is calculated. Upper limits are then set relating to the number of standard deviations (sigmas) above the sample population average. Many analysts put a caution at one or two sigmas and a critical at two or three sigmas. When one sigma is exceeded this means that the value from the test result exceeds 68 percent of historical samples. A result that alarms at two sigmas exceeds 95 percent of historical data. Three sigma exceedance corresponds to of 99.7 percent of the database.



Example: Historical Data of Iron Levels After 300 Hours on Oil

24	33	39	14	9
36	28	24	22	50
17	20	18	28	44
21	15	35	30	20

Average = $\bar{x}$ = 26.35 ppm
Sigma (σ) = 8.91

Example Limits

Hours on Oil	Caution $\bar{x} + \sigma$	Critical $\bar{x} + 2\sigma$
300	35 ppm	44 ppm
500	57 ppm	70 ppm
1000	104 ppm	121 ppm

Figure 6
Statistical Limits Are Keyed To Historical Oil Analysis Trends

Many commercial laboratories have large repositories of data spanning numerous machine types and models. These data permit the relatively easy calculation of national averages and corresponding population standard deviations (sigmas). In some cases the data can be conveniently sorted according to industry and application. These same databases can be used to assist in the setting of rate-of-change limits as well. Typical applications of statistical limits include elemental analysis of wear metals, ferrous density analysis (DR, PQ 90, etc.), and other common predictive oil analysis measures.

It is well known that many machines exhibit highly individual characteristics. They might trend high or low when compared to national averages. Data from a machine that is a low reader might not alarm early enough when national averages are used as the statistical base (false negative). Likewise, when a high reader is encountered (potential false positive), it may be well advised to adjust the statistical limit accordingly, or simply rely more heavily on rate-of-change limits.

Dealing With Data Noise: Data noise can mask or distort the target data parameter (and trend) often making it nearly invisible to detection. And, when data noise exists it can inhibit the ideal placement of certain alarms and limits. A machine that normally has a high level of wear particles in its lubricating oil is a good example. These particles do not represent current wear activity but are an accumulation of historical wear, possibly going back many months. This is a common situation when course filters or no filters are in use. This high concentration of wear particles constitutes noise for an oil analysis program.

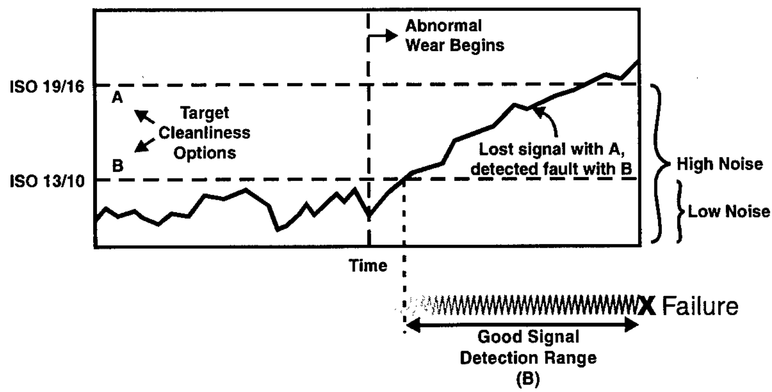


Figure 7
Clean Fluids Help Provide Improved Fault Detection Sensitivity

While the target signal (data) is current wear levels, these particles may be extremely difficult if not impossible to measure when they are mixed indiscriminately with historical wear debris. This equates to low signal-to-noise ratio. Crudely stated the fault signal is getting lost in the sauce. This situation is illustrated in Figure 7. When particle concentrations are controlled to an ISO 19/16 fault detection is poor. By comparison, the ISO 13/10 fluid translates to high-resolution detection, i.e., high signal-to-noise ratio. A similar problem occurs with infrared spectroscopy when weak absorption signals are lost due to inaccurate reference spectra and the presence of interfering materials in oil.

Summary: With the current trend of users taking control of the their oil analysis programs there has been a surge of interest in education. This has recently lead to an STLE (Society of Tribologist and Lubrication Engineers) committee being formed to offer oil analysis certification levels. While oil analysis education is often aimed at data interpretation it is no less important in the area of limit setting. In fact, limit setting and data interpretation are co-mingled activities. When oil analysis limits are properly set and the correct tests are performed at the right frequency, data interpretation is easy and efficient.

The strategic use of goal-based and aging limits enables proactive maintenance to be carried out at the highest level. Likewise, when rate-of-change and statistical limits are deployed, the benefits of early fault detection are achieved. The combination of these limit-setting strategies affords the broadest and most effective protection for the plant equipment and its lubrication assets. For more detailed information on how to set and use oil analysis limits contact the author at Noria Corporation, 2705 E. Skelly Dr., Suite 305, Tulsa, OK 74145.

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Diesel Engine Coolant Analysis, New Application for Established Instrumentation

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Abstract: Rotating disk electrode (RDE) arc emission spectrometers are used in many commercial, industrial and military laboratories throughout the world to analyze millions of oil and fuel samples each year. In fact, RDE spectrometers have been used exclusively for oil and fuel analysis for so long, that most practitioners have probably forgotten that when RDE spectrometers were first introduced more than 40 years ago, they were also routinely used for aqueous samples.

This paper describes recent work to calibrate and modify Rotating Disk Electrode (RDE) arc emission spectrometers for the analysis of engine coolant samples; a mixture of approximately 50% water and 50% glycol. The technique has been shown to be effective for the analysis of wear metals, contamination and supplemental coolant additives in ethylene and propylene glycol. A comparison of results for coolant samples measured by both Inductively Coupled Plasma (ICP) and RDE spectrometers will be presented. The data correlates extremely well on new and relatively clean coolants. However, not surprisingly, RDE results are sometimes higher for samples containing particles larger than a few micrometers.

This paper suggests that RDE spectrometers are appropriate, and sometimes preferred, for most types of coolants and certain types of aqueous samples. Actual field data is be presented to support the arguments.

Key Words: Engine coolants, coolant analysis, rotating disk electrode (RDE) spectrometers, inductively coupled plasma (ICP) spectrometers, debris monitoring, physical property monitoring.

Introduction: When an internal combustion engine burns fuel, heat is created at temperatures as high as 4000°F (2200°C). This heat must be removed by some form of cooling. The two most common ways to dissipate heat are by air cooling or liquid cooling. This paper discusses only the liquid cooling systems used in most modern engines.

A liquid cooling system contains the following components; radiator, fan, thermostat, water pump, engine water jacket and the cooling liquid. This paper will concentrate on the liquid contained inside the cooling system.

The analysis of used coolant samples has been a successful technique for scientific preventive maintenance. It is applicable to any closed loop cooling system, but is applied primarily to diesel and gasoline engines because they are the most likely component to suffer from a poorly operating cooling system. Overheating causes oil deterioration, oxidation, reduced lubricity and damage to all oil wetted components. The longevity of liquid cooled transmission and hydraulic system components are also dependent on a properly operating cooling system. A properly maintained cooling system not only prevents overheating but also maintains a constant engine temperature. Improperly maintained engine temperatures can result in the type of problems shown in Table 1.

Table 1 - Problems due to Improper Engine Temperatures

High Temperature Problems	Low Temperature Problems
• Pre-ignition • Detonation/Knock • Lubrication Failure • Burnt Pistons & Valves	• Unnecessary Wear • Poor Fuel Economy • Accumulation of Water & Sludge

Why Coolant Analysis: Most people don't give much thought to the condition of their engine coolant system until it is too late. More than 40% of all diesel engine maintenance problems can be attributed to poor cooling system maintenance [1]. Poorly operating cooling systems cause the engine to run hotter which in turn causes the lubricant to oxidize and loose it's lubricity thus causing abnormal wear in all oil wetted areas. The following is a list of reason why to do coolant analysis.

- Protect against gel formation
- Protect against corrosion and rust
- Protect against over/under concentration of SCA's
- Extend drain intervals
- Protect your engine
- Environmental/disposal concerns

Another factor that recently gained world-wide attention is the impact of used coolant disposal on the environment. Ethylene glycol is extremely hazardous if ingested by humans or animals. Because of this, most large users of coolants operate the coolants longer in order to reduce the need for disposal. Others have started recycling and reconditioning the used coolants. Because of this, the need for coolant analysis has increased dramatically over the past few years. Disposal of used coolants can be difficult and expensive and must be done in accordance with local, state or federal laws.

The following is the Cummins Engine Company recommended cooling system maintenance intervals: [2]

- Replace coolant filter at every oil change.
- Top off the cooling system at filter changes.
- Test/replenish SCA package at filter change.

- Test the coolant twice a year.
- Replace coolant every two years or 240,000 miles (6,000 hours).

The following is the Caterpillar Inc. (CAT SOS coolant analysis) recommended cooling system maintenance intervals: [3]

- Every 250 hours check glycol level, freeze and boil protection, SCA concentration, pH, and conductivity.
- Every 1000 hours or a minimum of twice a year check the same as above, plus identify metal corrosion, contaminant levels and built-up impurities.

Coolant Analysis: To be effective, a used coolant analysis program should determine both the coolant condition and the presence of any contaminants or debris. The coolant fluid can be used as a diagnostic medium as the coolant carries not only heat away from the engine parts but also carries fine debris from the interior surfaces of the cooling system. Analysis of the wear debris can provide important information about the condition of the internal parts of the cooling system. However, the condition of the coolant itself is important to know. Does the coolant meet specification? Is the SCA package correct? Is the coolant contaminated with solids, metal particulate or chemical degradation products?

In a modern condition monitoring program based on coolant analysis, a coolant sample is taken from a piece of equipment at periodic sampling intervals. Good and consistent sampling practice is extremely important. Samples should be taken from the radiator or block drain, never from the surge tank or coolant recovery bottle. The sample is sent to the laboratory for analysis. Based on the analysis, a diagnostic report is made and a recommendation is sent to the personnel responsible for the equipment. The report may show that everything is normal, warn of a possible problem or make a specific maintenance recommendation. The entire process, from sample taking to the diagnostic report, should take less than 24 hours. A sample report is shown in Fig. 1.

In a modern coolant analysis program, the data generated and collected by the laboratory is also used to provide periodic maintenance summaries. These reports can be statistical in nature and provide an insight to management personnel on the effectiveness of the program, efficiency of the maintenance department, repair status of equipment, recurring problems, and even information on the performance of coolants.

Condition monitoring by coolant analysis can be broken down into two main categories: Debris Monitoring and Coolant Condition Monitoring. Debris Monitoring spectrochemically measures the trace elements carried away from the cooling system by the coolant. Coolant Condition Monitoring determines if the coolant itself is fit for service based on physical and chemical tests. These two techniques, when combined with statistical trending and data-based management, provide a complete program of condition monitoring by coolant analysis.

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Coolant Analysis

Condition: Abnormal

COOLANT PERSON	Unit No. : 2
JOHN DOE COOLANT	Customer No. : 12804
123 YOUR STREET	Sample Date : 04/08/96
ANYTOWN,US 12345-0000	Received Date: 04/08/96
	Serial No. : 15689
	Lab No : 43544

Unit Description : COOLANT
Fluid Brand/Type :

**** Recommendation

RESERVE ALKALINITY APPEARS LOW.
FREEZE POINT APPEARS HIGH.
CORROSION METAL(S) ARE HIGH - RECOMEND DRAIN AND FLUSH COOLANT.
SUGGEST YOU ADJUST THE ANTIFREEZE/WATER MIXTURE TO A 50:50 MIXTURE.

Tests	Method	Result	Condition
COOLANT ELEMENTS			
PB		9.9	HIGH
CU		11	HIGH
FE		15	HIGH
AL		0.9	ACCEPTABLE
NA		2314	ACCEPTABLE
K		2237	ACCEPTABLE
BORON		1222	ACCEPTABLE
P		967	LOW
SI		32	ACCEPTABLE
MO		132	ACCEPTABLE
RESERVE ALKALINITY	D-1121	1.9	LOW
pH	D-1287	6.8	LOW
FREEZING POINT	D-1177	+5 F	HIGH
NITRITES		484 ppm	LOW
% ANTIFREEZE		25	LOW
VISUAL APPEARANCE		GREEN	ACCEPTABLE

Figure 1, Sample Coolant Analysis Report

Debris Monitoring for Coolants: Debris monitoring pertains primarily to the detection of metallic wear particles, corrosion products, degradation products and contaminants. Spectroscopy is the most widely applied technique for debris monitoring. Commercial labs in the USA have been using either ICP or AA spectrometers for coolant analysis. Table 2 lists elements routinely detected and quantified for coolant analysis.

Table 2 - Elements Routinely Detected and Quantified Coolant Analysis

Wear Metals	Contaminants	Additives
Iron	Silicon	Potassium
Zinc	Magnesium	Silicon
Lead	Calcium	Boron
Copper		Sodium
Aluminum		Molybdenum
Magnesium		Phosphorus

Table 3 lists the typical elements which are routinely analyzed and provides examples to their origin in a diesel engine cooling system.

Table 3 - Sources of Various Elements in Used Coolants

WEAR METALS
Iron (Fe) - Liners, water pump, cylinder block, cylinder head.
Zinc (Zn) - Brass from components.
Lead (Pb) - Solder in radiator, oil cooler, after cooler, heater core.
Copper (Cu) - Radiator, oil cooler, after collar, heater core.
Aluminum (Al) - Radiator tanks, coolant elbows, piping, spacer plates, thermostat housing.
Magnesium (Mg) - Cast alloys.

CONTAMINANTS
Silicon (Spectro Incorporated) - Dirt.
Magnesium (Mg) - Hard water scaling problem.
Calcium (Ca)- Hard water scaling problem.

ADDITIVES
Potassium (K) - Buffer.
Silicon (Si) -Anti-foaming agent, anti-corrosion for aluminum.
Boron (B) - pH buffer, anti corrosion for ferrous metals.
Molybdenum (Mo) - Anti-cavitation, silicate.
Phosphorus (P) - pH buffer, anti corrosion for ferrous metals.

The RDE/AES technique has been in use for over 50 years for the analysis of a variety of samples. Water samples were routinely analyzed by RDE spectrometers [4]. Low limits of detection were achieved by first concentrating the sample by evaporating most of the water by putting the water sample in an oven.

With the introduction of the ICP/AES technique in the late 1970's, water samples were no longer run on RDE spectrometers because of the significantly lower limits of detection as well as superior precision offered by ICP spectrometers. Concentration of water samples by evaporation was no longer necessary, at least not for routine samples, because the limits of detection were so very much lower.

For lubricating oil and fuel analysis, the RDE technique continued to be a preferred method due to its simplicity of operation and reliability. Sample introduction is simple. Both AA and ICP spectrometers require that the oil sample first be diluted, usually with kerosene, so that the sample can be nebulized to form an aerosol. The RDE technique also has the ability to more efficiently analyze the larger particulate in the used sample. RDE spectrometers lend themselves to on-site analysis in less than optimum working environments whereas AA or ICP spectrometers required a laboratory environment as well as more highly skilled personnel for their successful operation.

Recently, several RDE spectrometers for commercial customers were calibrated with coolant standards so that these spectrometers could be used not only for oil analysis but also for coolant analysis.

The limits of detection (LOD) that can be achieved on a RDE instrument are not as low as can be achieved using an inductively coupled plasma (ICP) spectrometer, but for coolant analysis low limits of detection are not very important since the results are rounded off to the nearest ppm for reporting purposes and sub-ppm levels are of no practical consequence.. Table 4 compares the LOD's for ICP and RDE spectrometers and shows that the RDE spectrometers are appropriate for coolant samples.

Table 4 - Limits of Detection

	RDE, Oil	ICP, Oil	ICP, Water	RDE, Water
Na	0.04	0.20	0.015	0.03
Mo	0.46	0.08	0.005	0.37
Mg	0.01	0.20	0.0002	0.01
P	3.00	0.50	0.008	3.20
B	0.07	0.01	0.002	0.13
Ca	0.03	0.03	0.0001	0.03
Cu	0.04	0.02	0.002	0.06
Al	0.35	0.02	0.001	0.43
Pb	0.80	0.10	0.02	0.75
Fe	0.23	0.02	0.002	0.21
Si	0.20	0.10	0.006	0.33
Zn	0.10	0.02	0.002	0.18

It may be of interest to note that the LOD's for oil are not substantially different than those obtained for water (or for water/glycol mixtures).

LOD's are not by any means the only measure of spectrometric performance. In the case of coolant analysis the purpose is to detect abnormal circumstances. LOD's have little to do with the quality of coolant analysis furthermore, real measurements are many times LOD so that LOD's much less than 1 ppm are not important.

The ICP technique measures only the most finely divided material, i.e., the material cannot be in the form of large particles. This is because the sample introduction system of an ICP spectrometer includes a spray chamber, the purpose of which is to remove the largest aerosol droplets generated by the nebulizer. The size of the aerosol droplets which reach the plasma torch where emission takes place are on the order of 1 or 2 µm. The RDE spectrometer, on the other hand, is able to detect somewhat larger particles, up to and beyond 10 µm in size.

Table 5 and Table 6 compare results obtained with an ICP spectrometer to results obtained on an RDE spectrometer on used coolant samples. Table 5 is a comparison of used coolant samples that were relatively clean, (no particulate could be visibly detected). Table 6 is a comparison of used coolant samples where particulate could be visibly detected. The data clearly show that if particles are present the results for the

wear metals and contaminants are substantially higher when the sample is run on the RDE spectrometer. It may be concluded from this data that neither instrument is entirely quantitative for these samples because there will typically be some fraction of larger particles that is not completely measured by either an ICP or RDE spectrometer. Nevertheless, the purpose of the analysis is served by indicating which coolant systems are in distress. It may be argued that since the RDE spectrometer is more responsive to large particles it is more capable of indicating abnormal coolant conditions than an ICP spectrometer.

Coolant Physical Property Monitoring: The second part of an effective coolant analysis program is coolant condition monitoring. Through periodic sampling of the coolant, the laboratory can determine the effectiveness and remaining life of the coolant based on additive degradation and contamination analysis.

ASTM (American Society for Testing and Materials) tests are mostly written for quality control and quality assurance requirements of new and sometimes used coolants. Therefore, ASTM procedures are often modified to reduce analysis times in the interest of economics. The number and type of tests that are performed on a used coolant sample vary. Table 7 summarizes the physical property tests performed by the typical used coolant analysis laboratory.

Table 5 - ICP/RDE Comparison of "Clean" Coolant Samples

INST	Al	Cu	Fe	Pb	Zn	Mg	Ca	Si	Mo	P	B	Na
RDE	1.1	0.4	0	0	0	0.5	0	47.6	18.6	590	389	2069
ICP	0	0	0	0	0	0	0	41	19	406	248	1078
RDE	14.8	6	7.8	8.7	2	0	0	37.6	0	122	263	1546
ICP	6.7	0	3.8	3.2	0	0	0	26	0	90.2	217	914
RDE	1.3	0.4	0	0	0	0.1	0	34.8	0.2	511	649	2541
ICP	0	0	0	0	0	0	0	28	0	315	421	1309
RDE	0.5	0	0	0	0	0	0	3.2	13.5	77.5	615	2409
ICP	0	0	0	0	0	0	0	3.7	18	60	480	1283
RDE	0.4	0.7	5.7	7.1	1.3	0.5	0.8	40	58.9	984	635	2835
ICP	0	0	2.7	2.8	0	0	0	26	44	585	345	1385
RDE	0.8	0.7	1	0	0	0	0	3.7	0	445	325	1364
ICP	0	0	0	0	0	0	0	3.6	0	335	213	852
RDE	0.3	0.9	0.6	6	1.9	0.4	12.1	61	1.2	122	840	5972
ICP	0	0	0	2.6	0	0	3.6	43	0	74	515	2650

Table 6 - ICP/RDE Comparison of Coolant Samples Where Particles Were Detected

INST	AL	CU	FE	PB	ZN	MG	CA	SI	MO	P	B	NA
RDE	0.2	39	0	39	8.7	0.9	0	53.6	0	1677	630	5440
ICP	0	12	0	17	2.5	0	0	34	0	1163	321	2733
RDE	11	23	60	2.8	4.3	1.3	0	34.2	2.5	61.8	806	3365
ICP	6	5.6	37	0	0	0	0	23	4	53.7	672	2134
RDE	0.5	47	0	0	0	0.2	0	59	23.3	583	1415	6471
ICP	0	8.7	0	0	0	0	0	30	15	271	748	2552
RDE	2	1	1	4.9	2.8	1.3	5.8	42.4	68.5	326	1088	5013
ICP	0	0	0	2.2	0	0	0	29	58	203	678	2668
RDE	0.9	16	75	25	40	0.9	4.2	12.4	0.2	12.1	1368	5118
ICP	0	2.3	28	7.5	19	0	0	5.2	0	12.5	870	2495
RDE	1.1	1.7	24	2.5	2.5	0.4	0.1	24.5	66.3	709	385	1652
ICP	0	0	7.5	0	0	0	0	19	61	522	232	959
RDE	9.4	12	114	49	6.9	10	66.4	29.4	0.6	948	1424	6567
ICP	0	0	25	8.9	0	2.2	12	12	0	561	746	2904
RDE	0	28	130	70	14	3.7	1.2	39	7	327	322	1671
ICP	0	0	47	18	6.7	0	0	32	8.7	222	211	939
RDE	5.7	44	1.5	3.4	28	27	269	150	260	2110	751	3585
ICP	0	12	0	0	7.6	7.4	44	83	193	1315	334	1564

Table 7 - Typical Physical Property Tests for Used Coolant Analysis

- pH, ASTM 1287
- Reserve Alkalinity, ASTM D1121
- Percent EG/PG
- Freeze/Boiling Point
- Nitrite, ppm NO2
- SCA Levels
- Total Dissolved Solids (TDS)
- Appearance

pH: Measures the acidity or alkalinity of the used coolant sample. This can be measured by performing ASTM D1287, which is very precise. The use of an inexpensive pH meter can provide quick and accurate results in a non-laboratory environment. Most pH meters have the capability to measure the conductivity of the coolant which also can be used to determine the percentage of TDS. Most major engine manufacturers recommend coolant pH levels between 8.5 to 10.5. If pH levels fall below 8.0 rapid nitrite depletion will occur. Coolant pH levels above 11.5 will corrode aluminum and promote scaling[2].

Reserve Alkalinity: Measures the amount of alkaline inhibitors present in the used coolant. This gives an indication of the coolant's ability to provide corrosion protection. This test can be performed by ASTM D1121. If the buffering agents are not at correct levels, corrosion and rapid additive depletion will occur due to a reduction in pH values. The result will be cylinder liner pitting.

Percent Antifreeze EG/PG: This test uses a refractometer to quantify the amount of EG/PG in a coolant sample. Most major engine manufacturers recommend coolants composed of 50/50 water/glycol solution to provide satisfactory freeze and boil point protection. An operating range of 40 to 60 % antifreeze is acceptable, however, the use of antifreeze in concentrations over 65% may cause SCA drop-out, water pump seal damage and engine overheating.

Freeze/Boiling Point: Once the percent of EG or PG is determined, the freeze and boiling point can be calculated by using charts provided by the antifreeze manufacture. Freeze point can also be measured by performing ASTM D1177. If the percent antifreeze is not known, an inexpensive hydrometer can be used to measure the density of the coolant and then calculate the freeze point. The amount of freeze protection required should be based on the lowest expected temperature in your region.

Nitrites/SCA Package Analysis: The analysis of the primary corrosion inhibitor, nitrite, can be performed by various tests. The most accurate method is by ion chromatography. For the most accurate results this test must be performed in a laboratory. The second method is the colormetric analysis with nitrite test sticks. This is a very quick and easy way to measure the concentration of NO_2. Fleetguard offers a test stick that will measure nitrites (NO_2), molybdates (MoO_4) and freeze point protection colormetricly on the same test stick. As with all elements contained in the SCA package, the concentrations must remain within 10% of the new coolant SCA additive level.

Total Dissolved Solids (TDS): This is a measurement of the dissolved solids in the coolant. The dissolved solids are composed of the basic inhibitor chemicals, silicates, active SCAs, spent SCAs, contaminants and water hardness compounds[2]. The higher the dissolved solids the higher the conductance. The percentage TDS can be quantified with a conductivity meter. This meter will also be capable of measuring the pH of the coolant. Cummins recommends a maximum of 5% TDS, higher levels may cause water pumps seal failure[2].

Appearance: This quick and easy test records the overall condition, color and visible contamination of the coolant. Color is important because most manufacturers identify coolants by color. It is important to notify maintenance personnel if oil or large particles are present in the coolant sample.

Conclusion: RDE spectrometers, when appropriately calibrated, may be used as part of a condition monitoring program based on coolant analysis. The same instrument as used for used oil analysis can be modified and calibrated to also effectively analyze coolants. The added capability provides the laboratory with an supplementary tool to increase its capabilities and effectiveness.

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Loss-Prevention and Risk-Mitigation by
Reducing False-Alarms in
Equipment Protection Systems

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Abstract: Like death and taxes Equipment Protection System failures (alarms) are undesirable, unpredictable, unwarranted, and unexplainable. 95% of industrial[1] alarms are false, 99% in aircraft, and 99.9% in security systems. They excite management, incite environmentalists, spur regulatory agencies, and frighten many. Product loss and wasted resources are obvious consequences. Not so obvious is the negative impact on safety. Fail-safe... shutdown upon failure... *doesn't make the situation safer*. Instead, there's a high-risk of damage or catastrophe during restart.

Key Words: Fault-tolerant; Reliability; Fault-diagnostics; Predictive maintenance.

Technological Advance Inadequate: Pneumatics and relays were used initially. The '50s saw solid-state, PLC's emerged in the '70s, PC's in the '90s. This trend is a Paradigm-Shift... the unquestioned use of habitually employed hi-tech. Computers have improved, but I/O devices haven't... performance is still poor. This paradox is evident in the Process industry... advance is evident, but *false-trip rates haven't decreased.*

Failures Are Predictable: Overt failures are simple and obvious. Covert ones, aren't. There are just two types: *Electrical-* opens, shorts, grounds, corrosion, maloperation, etc; and *Transients-* intermittents, glitches, vibration, power disturbances, etc.

The Good, The Bad, and The Ugly: Reliability equations use a 2-state analysis, that is, components are either GOOD or NO-GOOD. *But, the results of this technique can be in error.* In reality there are 3-states: GOOD (successful); BAD (*unwarranted*); and UGLY (*unresponsive*), which require a 3-state analysis.

Probabilistic Engineering Techniques to Reduce False Alarms:

- The anatomy of a Protection-System is presented and its parameters evaluated.
- 2-state and 3-state analyses are compared.
- Sacred-cows are exposed, including the popular software-based TMR scheme.
- Mathematical models considering *Good, Bad, & Ugly failure-modes* are developed.
- Examples of the technique are illustrated.

The Anatomy of an EPS System: Fig. 1 identifies major elements of an EPS system.

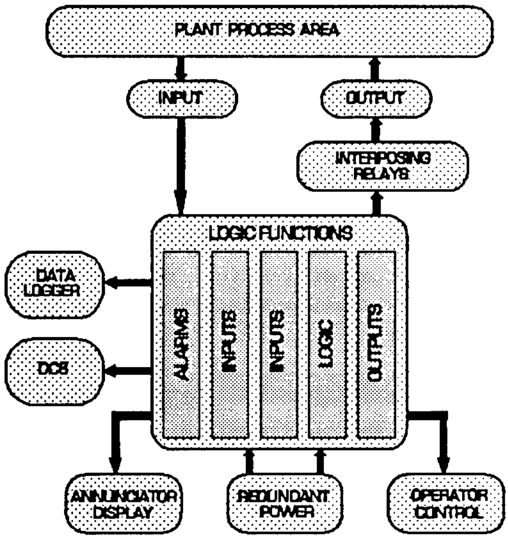

Figure 1: ESD Block Diagram.

Essentially an EPS consists of seven major components:

- Input, which are the tripping-variable sensors, their connecting field wiring and their terminations.
- Logic, which receives, processes, and then executes the pre-programmed logic. It may also include analysis of the final element's response (feedback).
- Output, which are the final output-action actuating devices (valves, breakers, etc.) their wiring, and their terminations.
- Operator Control, which provides the operator with the means to bypass, trip, reset, arm, etc.
- Operator Display, which provides concise information regarding EPS status.
- Data Acquisition, which sequentially tags and time-stamps the EPS events.
- Power Supply, which provides both the logic-level and output-action power.

2–State Probabilistic Engineering Analysis: Fig. 2, illustrates that with a 2–state analysis (sensor is Good or NoGood) the probability[5] of system success increases with the addition of redundant elements, which is the perception with voting configurations:

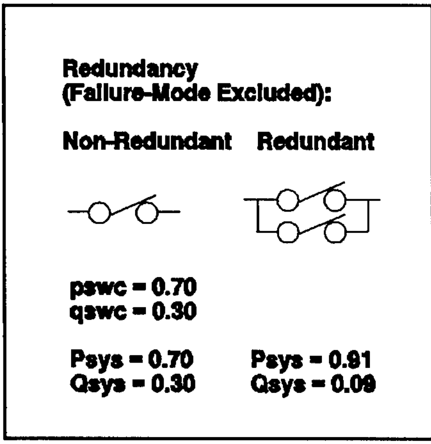

Figure 2: Two–state analysis.

Where:

p_{swc}=	The probability of a sensor being GOOD (successful).
$q_{swc}=1-p_{swc}$=	the probability of a sensor being NO-GOOD (unsuccessful).
$P_{sys}=p_{swc}$=	the probability of system success.
$Q_{sys}=q_{swc}$=	the probability of system failure.

The probability of success formula accounts for 2 states, one working, the other not. The Good and No–Good probabilities are p_{swc}, and q_{swc}, respectively. In this example P_{sys} increases to 0.91, a formidable improvement over the single switch case. Fig. 2 illustrates that in a 2–state analysis[6] the *probability of system success does increase with redundancy.*

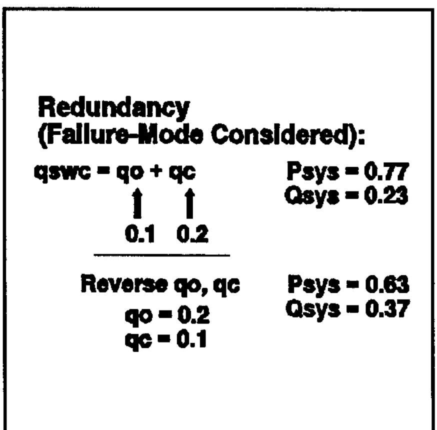

Figure 3: Three–state analysis of a switch system with overt and covert failures considered.

where:

$p_{swc}=0.7$=	the probability of a sensor being GOOD (successful).
q_o = 0.1=	the probability of the sensor's BAD (unwarranted).
q_c = 0.2=	the probability of the sensor's UGLY (unresponsive).

The probability of success formula has been modified (see Appendix) to include a sensor's fault–modes, overt and covert. The fault–mode probabilities are q_o, and q_c, respectively. Applying these values to the first example, the probability of system success becomes, P_{sys} = 0.77, which is considerably poorer than the expected 0.91. And, if q_o and q_c are interchanged the situation worsens... P_{sys} is further reduced to 0.63. In summary, when fault–mode is included, an EPS relying on redundant switches, *does not automatically result in higher reliability.*

Design Factors Affecting EPS Performance: Other design factors affect system performance and therefore must be considered. They include transients, connecting wire failures, termination failures, control power source grounding preference, and trip-mode philosophy.

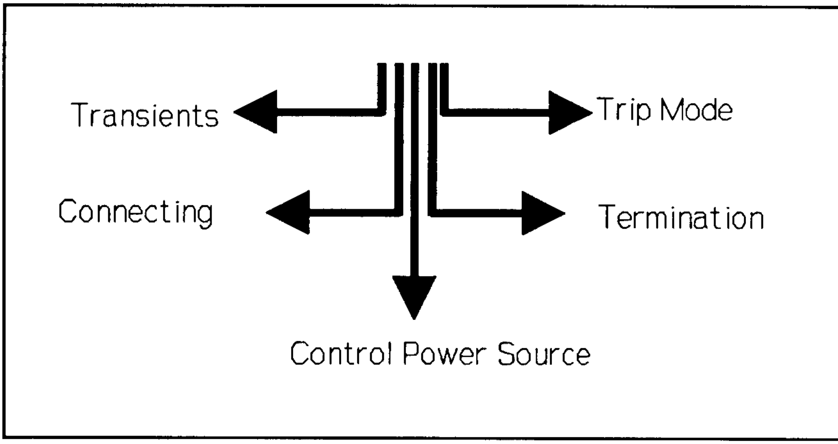

Figure 4: Factors effecting ESD performance.

Following is a description of each of the factors noted above:

- Transients include contact bounce, relay chatter, power dips, radio frequency interference (RFI), electromagnetic interference (EMI), X-ray effects, etc.
- Control-power source grounding refers to whether it is intentionally grounded or floating. Alternating-current control-power sources are usually grounded, while Direct-current control-power sources can be either grounded or floating.
- Trip-mode philosophy refers to the EPS response-mode: Energize-to-Trip or **ETT**, sometimes referred to as production-safe; and Deenergize-to-Trip or **DTT**, often referred to as fail-safe.
- Connecting wire failures consist of open-circuits, short-circuits, and ground-faults.
- Termination failures include corrosion or accidental bridging of wire-strands at adjacent terminals.

Many plants with machinery EPS (power plants in particular) use the ETT philosophy because of the *perception* that ETT is blind to overt or false-trip failure-modes. Conversely, boiler and furnace flame-guard systems have DTT as required by National Fire Protection Association (NFPA) Standards since DTT is better able to prevent covert or catastrophic failure-modes. An explanation of each type follows.

Example of a Typical ETT Input Loop: Consider the circuit shown in Fig. 5. A normally-open sensor is powered by a floating power-source. This circuit must *close to energize* the trip relay, which in turn actuates the final element such as, a valve, breaker, etc. Transients like power dips or bounce, will not cause false-alarms. On the other hand an open circuit in the sensor's connecting wires or its protective fuse operates prematurely, then the EPS will not trip when required, causing a catastrophic failure.

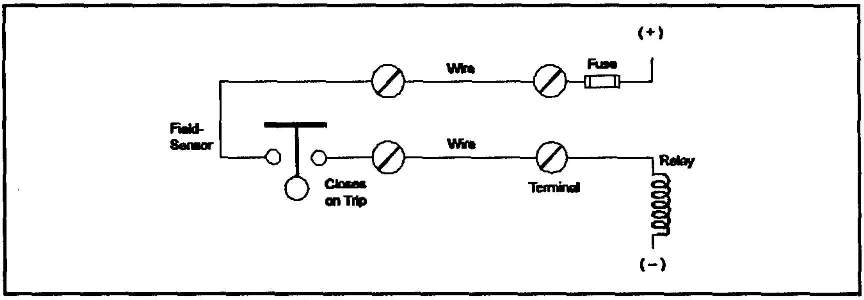

Figure 5: Energize-to-Trip (ETT) loop.

Example of a Typical DTT Input Loop: Now consider the circuit shown in Fig. 6. A normally-closed sensor is powered by a grounded power-source. This circuit must *open to deenergize* the final element. The system will fail catastrophically if the sensor, its connecting wires or its terminations are short-circuited and none of the faults are detected. Furthermore, any open-circuit, ground-fault, contact-bounce, premature fuse operation, or power dip will result in a false-trip.

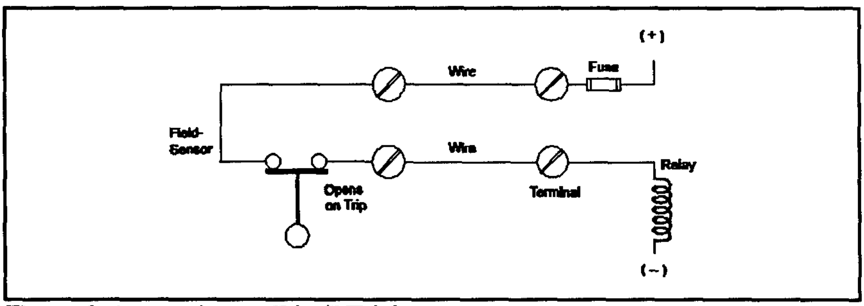

Figure 6: Deenergize-to-Trip (DTT) loop.

Thus, Fig. 5 is better for reducing effects of faults resulting in false-alarms, but it masks those failures which could result in catastrophic failure. Conversely, Fig. 6 has opposite characteristics. Each method has features useful in mitigating particular consequences. ETT is more widely used in machine EPS where inadvertent loss of continuity of the machine is intolerable. Conversely DTT finds use in *fired-equipment* such as, boilers, furnaces and heaters where the consequences of failure to trip could be disastrous.

3-State Analysis (w/o Diagnostics) for Machinery: Data obtained from IEEE[7], AICE[8], MIL-Handbook[9], and US Navy Handbook[10] were used to develop Table Nº 1. Five system configurations are considered, all based on DC relay logic, ETT trip-mode, a floating control-power source, but, fault-mode detection is excluded:

Table Nº 1: Energize-To-Trip System Performance.

LOGIC	P_{swc}	P_{sys}	Q_{ftr}	Q_{cat}
1 of 1	0.95740	0.88978	0.01927	0.09095
1 of 2	0.97439	0.95356	0.03817	0.00827
2 of 2	0.94041	0.82601	0.00037	0.17362
2 of 3	0.99686	0.97559	0.00110	0.02331
2 of 4	0.99898	0.99502	0.00217	0.00280

Where:

1 of 1 = 1/1, or 1oo1, or One-of-One
1 of 2 = 1/2, or 1oo2, or One-of-Two
2 of 2 = 2/2, or 2oo2, or Two-of-Two
2 of 3 = 2/3, or 2oo3, or Two-of-Three (TMR).
2 of 4 = 2/4, or 2oo4, or Two-of-Four (Nuclear).

P_{swc} = sensor success probabilities. Calculated using the 2-state technique, considers only that the sensor is Good or NoGood, and ignores the effects of fault-mode.

P_{sys} = system success probabilities. These are calculated with the 3-state method and includes fault-mode effects of the sensor, interconnecting wiring, terminations, control-power source grounding preference, and trip-mode philosophy.

Q_{ftr} = false-trip failure probabilities.

Q_{cat} = catastrophic failure probabilities.

3-State Analysis (w/o Diagnostics) for Fired-Equipment: To illustrate that different results will be obtained for boiler or heater EPS's, the same failure-rates and configurations are used to develop Table Nº 2. This time, however, design factors are based on AC relay logic, the DTT Trip-mode philosophy, and a grounded power source:

Table Nº 2: Deenergize-To-Trip System Performance.

LOGIC	P_{swc}	P_{sys}	Q_{ftr}	Q_{cat}
1 of 1	0.97227	0.88949	0.08306	0.02745
1 of 2	0.97488	0.84002	0.15922	0.00075
2 of 2	0.96967	0.93895	0.00690	0.05415
2 of 3	0.99885	0.97823	0.01955	0.00222
2 of 4	0.99906	0.96297	0.03695	0.00008

Impact Of Fault-mode Detection On EPS Performance: Will fault-mode detection still satisfy the EPS requirements without compromising safe and continuous operations? Different philosophies were a reasonable course of action to meet the unique and divergent operational requirements of machinery and fired-equipment shutdown systems. However, with the advent of fault-mode detection and the application of 3-state analysis, now both applications can be served with one type of EPS. A major advantage is that operator and technician understanding of the system is simplified. They do not need to wear two hats, one for machinery, the other for fired-equipment protection systems.

The same failure-rates which were used to develop Tables Nº 1 and Nº 2, were used in the development of the Probability values shown in Table Nº 3, except that failure-rates were adjusted to exclude all detectable failures. Four of the protection system types evaluated earlier were evaluated. A fifth type, HIQ, was also evaluated. It exceeds 2 of 3 or TMR expectations for half the cost. Following is a list of the 5 configurations based on solid-state discrete-logic, the DTT philosophy, powered from a grounded control-power source, and with fault-mode detection and diagnosis included:

Table Nº 3: Fault-Detection System Performance.

LOGIC	P_{swc}	P_{sys}	Q_{ftr}	Q_{cat}
SNV	0.97227	0.96472	0.02013	0.01514
DNV	0.97488	0.95991	0.03986	0.00023
DUV	0.96967	0.96969	0.00004	0.03027
TMV	0.99885	0.99919	0.00012	0.00069
HIQ	0.99892	0.99937	0.00016	0.00047

Where:

SNV = Simplex-Non-Voting.
DNV = Duplex-Non-Voting.
DUV = Duplex-Unanimous-Voting.
TMV = Triplex-Majority-Voting.
HIQ = High-Integrity-Quad (2x1/2) Voting.

This example indicates that the probability of system success, P_{sys}, of an EPS having fault-mode detection, shows considerable improvement over the earlier examples which do not have fault-mode detection. Correspondingly, the False Trip-rate Probability, Q_{ftr}, and the Catastrophic Failure Probability, Q_{cat}, are substantially reduced.

3-State Analysis On A Large Turbo-Machine: This case illustrates the application of the 3-state analysis to an FCCU machinery-train located in a Gulf-states area refinery. The goal... to achieve a four-year continuous run. Obviously, false-trip reduction of the EPS was an essential consideration. The original system is compared to one having fault-mode detection and diagnostics. Failure-rate data shown is specific to the trip variable's input-sensor type:

CASE STUDY: EPS PERFORMANCE STUDY COVERING GULF-STATES-AREA REFINERY FCCU MACHINERY-TRAIN

Scope of Study: Original Relay System vs Fault-detection Equipped EPS System
Basis of Study:
Base Case: AC Relays; ETT Logic; Grounded-Power; w/o Fault-Mode Detection
Alt' Case: Solid-State; DTT logic; Grounded-Power; with Fault-Mode Detection

<--- INPUT SENSOR --->	<----- ORIGINAL (Base Case)			------>	<---- FAULT DETECTION EPS			-------->
	Logic	Psys	Qftr	Qcat	Logic	Psys	Qftr	Qcat
PROCESS VARIABLES								
Regen'r Pressure	1/1	0.88970	0.01150	0.09880	HIQ	0.99981	0.00001	0.00018
Lube Oil Pressure	1/1	0.88970	0.01150	0.09880	HIQ	0.99981	0.00001	0.00018
Separator Inlet Temp	1/1	0.89887	0.01530	0.08583	HIQ	0.99981	0.00015	0.00004
Instr Air Pressure	1/1	0.88970	0.01150	0.09880	DUV	0.98642	0.00001	0.01357
AIR BLOWER VARIABLES								
Axial Displacement	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Rad Vibr'n, Gear End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Rad Vibr'n, Xpnd End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
EXPANDER VARIABLES								
Axial Displacement	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Rad Vibr'n, Cplg End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Rad Vibr'n, Idle End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Overspeed	1/2	0.95967	0.03188	0.00846	DUV	0.99006	0.00003	0.00991
BULL GEAR VARIABLES								
Rad Vibr'n, Cplg End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Rad Vibr'n, Idle End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
PINION GEAR VARIABLES								
Axial Displacement	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Rad Vibr'n, Gear End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Rad Vibr'n, Xpnd End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
MOTOR/GEN'R VARIABLES								
Rad Vibr'n, Cplg End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Motor Run Contact	1/1	0.87932	0.01916	0.10152	SMV	0.98471	0.00004	0.01525
AVERAGE VALUES	---	0.92677	0.03978	0.03345	---	0.98961	0.00007	0.01032
EQUIV FAILURE-RATE	---	8.68 per million hours			---	1.19 per million hours		

PERFORMANCE IMPROVEMENT FACTORS	Original	Altern'v
OIF, Overall Improvement Factor	1.0	7.3
FTR, False-Trip Reduction Factor	1.0	591.7
CRF, Catastrophic Risk Factor	1.0	0.3
BCR, Benefit-To-Cost Ratio	1.0	6.7

DEFINITIONS:
Psys = The probability of System success.
Qftr = The probability of System false-trips.
Qcat = The probability of System catastrophic risk.

OIF = The ratio of the Original-system equivalent failure-rate to the Alternative-system equivalent failure-rate.
FTR = The ratio of the Original-system average false-trip failure-rate, Qftr, to the Alternative-system average false-trip failure-rate.
CRF = The ratio of the Alternative-system average catastrophic failure-rate, Qcat, to the Original-system average catastrophic-failure-rate.
BCR = The ratio of the Overall-Improvement-Factor achieved, to the cost (normalized) paid for the improvement.

Result: This unit not only achieved its original four-year goal (1,400 days), but thus far, has reached 6,800 days, *more than 18-years*, without failure.

The Sacred Cows of EPS Design: When it comes to design of EPS, the only ones who can change rules are people most involved and responsible... engineers who design them.

"Sacred cows" are the untouchable designs, specifications, etc., that EPS designers cherish most. They are easy to recognize... *anything that is vehemently defended with "we've always done it this way."* Some of the most recognizable are:

- Triplicate Modular Redundancy (TMR).
- Personal Bias Establishes Trip-Mode Philosophy.
- Designers Disregard Operators' Input[11].
- Floating Control-Power Sources Improve Probability of success.
- Uninterruptible Power Systems (UPS) Eliminate False-alarms.
- Flame-Scanners and Vibration Monitors Are Notorious for Causing False-alarms.

What About This TMR "Stuff" Anyway: Imagine that in 1994 you bought a new vehicle and to keep the engine in good working order you perform monthly engine tune-ups. In 1997, you drive that car to the JOAP Conference 500 miles away. Would you expect the vehicle to perform exactly as it did in 1994? No, because in order for the car to successfully complete the trip, the tires, shocks, brakes, etc., also need to be maintained in addition to the monthly tune-up.

TMR or Triplicate-Modular-Redundancy is the most touted of EPS configurations. The fallacy lies in how its performance is measured. MTBF is a valid means of evaluation, but, it falls short when used as a measure of TMR performance. MTBF which ignores the effects of input and output device failure probabilities is a misleading indicator of performance. When considering the time-dependency effect of not only its computer (example, the car's engine) but also upon its input/output components (example, the car's tires, shocks, etc.), a surprisingly different performance picture emerges, as shown below:

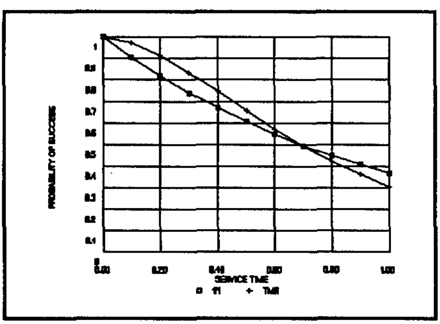

Figure 7: Comparison of 1/1 and TMR.

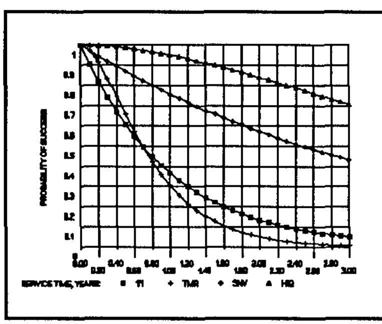

Figure 8: Comparison of 1/1, TMR, SNV, and HIQ.

Fig. 7, illustrates the fallacy of the TMR system by comparing it to the 1/1 system over a mission or service time of one year. *Input device failure probability is included.* Fig. 7 shows that the probability of success of the TMR is better than that of 1/1, until the cross-over point at eight months (t= 0.693). The TMR system declines after this point. If the 1/1 system sensor is maintained yearly, then, TMR's three sensors must be maintained at eight month intervals in order for it to maintain its lead in probability of success. These additional considerations negatively impact on TMR's Overall-Improvement-Factor. Its Benefit-to-Cost ratio is also reduced because the maintenance multiplier is 4⅓ (3+0.693) times that of 1/1.

Fig. 8, compares four systems, 1/1, TMR, SNV, and HIQ, over a longer service-time of three-years. The probability of success curves show that systems with fault-mode detection yield much better performance. After about 2½-years, SNV's probability of success equals that of 1/1 and TMR at their cross-over point. Thus, they are out-performed by twenty-two months. HIQ illustrates the impact of higher-level redundant configurations with fault-detection. Although not shown on the graph, at 4½-years HIQ's probability of success is still above the value at 1/1 and TMR cross-over point.

The conclusions of this presentation are:

- To effectively evaluate performance, catastrophic-risk and false-alarm modes of Inputs and Outputs must considered. This necessitates the use of a 3-state analysis (Good, Bad, & Ugly) instead of the usual 2-state (Good & NoGood) one.
- An EPS, using a DTT mode philosophy with an intentionally grounded DC power source, and fault-mode detection, will achieve the highest Overall-Improvement-Factor and False-Trip-Reduction factor and the lowest Catastrophic-Risk-Factor.
- Of all logic configurations investigated, the HIQ configuration results in the highest Overall-Improvement-Factor, the highest False-Trip-Reduction factor, the lowest Catastrophic-Risk-Factor, and the highest Benefit-to-Cost-Ratio.
- The fallacy of TMR claims when used for EPS, is that they do not include input/output probability of success over an anticipated mission or service-time. When these parameters are included, then TMR systems will show decreased probability of success factors, and a reduced Benefit-to-Cost-Ratio.
- EPS can be configured with the safer Deenergize-to-Trip logic without the fear or concern about power dips or transients causing false-alarms.
- Case studies for typical fired-equipment EPS like boilers and heaters, also show marked improvements, similar to those of turbo-machinery EPS.
- Mathematical models used to evaluate EPS designs should consider the following: sensor type (eg, pressure, flow, temperature, etc); logic configuration (non-voting, 1/1, 1/2, etc); overt-failure and covert-failure effects; control-power parameters (AC, DC, grounded or floating); logic element selection (relay, solid-state, software-programmable types); and output-action devices (starter, valve, breaker, solenoid, AC, DC, grounded or floating).

APPENDIX: 3–State Probability of Success Analysis

An EPS input protective device, such as a pressure sensor, has *one working state* and *two failure states*. Its two fault–mode states can be described as "o" for overt (unwarranted tripping) or "c" for covert (unresponsive to demand). EPS elements (devices) are connected in parallel or in series in order to implement various logic configurations.

A) Parallel Networks

A parallel system comprised of active, independent, 3–state devices will only fail if all devices fail in the overt–mode, q_o, or at least one of its devices fails in the covert–mode, q_c. The system time–dependent Probability of Success, $P_s(t)$, is given by

$$P_s(t) = \prod_{i=1}^{m} [1 - q_{oi}(t)] - \prod_{i=1}^{m} q_{ci}(t) \tag{1}$$

where:

- t is time.
- n is the number of 3–state devices in parallel.
- q_{oi} is the overt–mode probability of the *i*th device at time t.
- q_{ci} is the covert–mode probability of the *i*th device at time t.

The system overt–mode probability, Q_{ftr}, is given by

$$Q_{ftr}(t) = 1 - \prod_{i=1}^{m} [1 - q_{oi}(t)] \tag{2}$$

Similarly, the system covert–mode probability, Q_{cal}, is given by

$$Q_{cal}(t) = \prod_{i=1}^{m} q_{ci}(t) \tag{3}$$

For the *i*th device overt–mode and covert–mode failure–rates, λ_{oi} and λ_{ci}, respectively, and equating their sum to A_i, then its time–dependent relationship is given by

$$P_s(t) = \prod_{i=1}^{m} [1/A_i]\{\lambda_{oi} + \lambda_{ci}\, e^{-B}\} - \prod_{i=1}^{m} [\lambda_{oi}/A_i]\{1 - \lambda_{ci}\, e^{-B}\} \tag{4}$$

where:

$$B = A_i t \tag{5}$$

B) Series Networks

A series system is the reverse of the parallel one. It will only fail if all of its elements fail in a covert–mode or any one element fails in an overt–mode. Then, by duality, its system time– dependent Probability of Success, $P_s(t)$, is given by

$$P_s(t) = \prod_{i=1}^{m} [1/A_i]\{\lambda_{ci} + \lambda_{oi}\, e^{-B}\} - \prod_{i=1}^{m} [\lambda_{ci}/A_i]\{1 - \lambda_{oi}\, e^{-B}\} \tag{6}$$

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PFPE, A Unique Lubricant for a Unique Application

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Abstract: PFPE (Perfluoropolyether) is a clear colorless fluorinated synthetic oil that is nonreactive, nonflammable, safe in chemical and oxygen service, and is long lasting. PFPE grease is made by mixing different types of non-soap thickeners with the PFPE base oil. This paper highlights the unique properties (physical and chemical) of the PFPE as well as its unique application in areas where other lubricants are deficient. This paper includes methods of applying PFPE in oil and grease form, manufacturing of PFPE, and the benefits of using PFPE lubricants. Also, it includes a general overview of a hybrid grease--a grease suitable for less severe applications than PFPE yet superior to conventional greases produced by combining fluorinated greases with mineral/synthetic oils.

Key Words: Thermogravimetric analysis (TGA); Fourier transform infrared spectroscopy (FTIR); X-ray fluorescence (XRF); synthetic lubricant; lubricant degradation; lubricant properties; grease plating; vacuum impregnating, hybrid greases.

Introduction: PFPE, also called perfluoroalkylether (PFAE), or perfluoropolyalkylether (PFPAE), oils and oil-based greases are being used with an increasing frequency in spacecraft systems because of their favorable properties which include a wide application temperature range (see figure II), a good viscosity index, and general chemical inertness. The chemical inertness, however, must be evaluated in the light of extended satellite mission lifetimes and the rigors of operation in the orbital environment.

As with any other grease, PFPE grease consists of an oil, thickener, and in some cases additives. The base oil is the key component in the lubrication regime. The base oil is a polymer with a molecular weight range from 3000 to 13000 gm/gm mole, with viscosities varying from 2 cSt to 100 cSt at 100°C. The chemical structure of the base oil can be straight chain or branched chain (Z and Y fluids respectively) (see table I). The physical properties of the base oil depend on the structure of the polymeric chain. The thickener is usually Polytetrafluoroethylene (PTFE), or if the application requires a high thermally stable grease various types of fumed silica can be used.

CHEMICAL STRUCTURE OF PFPE

HYDROFLUOROETHYLENE : (HEPO)

$$F\text{-}(\text{-}\underset{\substack{|\\ CF_3}}{CF}\text{-}CF_2\text{-}O\text{-})_n\text{-}CF_2\text{-}CF_3 \qquad n = 10\text{-}60$$

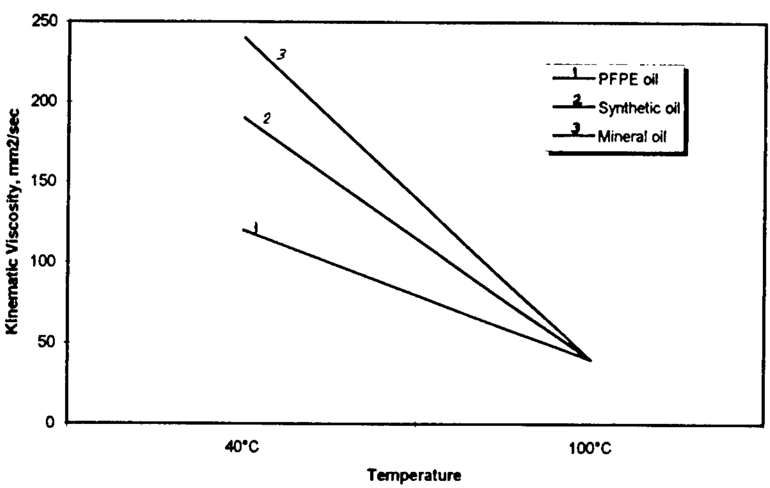
TETRAFLUOROETHYLENE : (TFE)

$$CF_3\text{-}(\text{-}O\text{-}CF_2\text{-}CF_2\text{-})_p\text{-}(\text{-}O\text{-}CF_2)_q\text{-}OCF_3 \qquad p/q < 0.8$$

PERFLUOROTRIMETHYLENEOXIDE : (PFTMO)

$$F\text{-}(\text{-}CF_2\text{-}CF_2\text{-}CF_2\text{-}O\text{-})_n\text{-}CF_2\text{-}CF_3 \qquad n = 10 - 60$$

Table (I)



Viscosity-temperature slope (ASTM) as a function of kinematic Viscosity at 40°C and 100°C for different oils.

Figure I

BENEFITS OF PFPE LUBRICANTS

Bearing cleanliness: It is important to select the proper PFPE for the specific application. Both PFPE oil and grease lubricants provide a viscous, hydrodynamic film sufficient to support the load and separate ball from the raceway in bearing applications. Usually greases are displaced during the initial run in and remain fixed in place during their life. The oil in the thickener will bleed into the raceway. In high speed bearings, the oil is agitated severely producing an oil mist. This also occurs in slow speed bearings but to a lesser extent. This oil mist can migrate outside the bearing cavity. Therefore, it is preferable to use an inert oil, like one of the PFPE oils.

Excellent outgassing : PFPE is the best lubricant for the clean room, in the electronics industry because of it's very low outgassing properties compared to any other lubricants, and it does not outgas any hydrocarbons. Hydrocarbons will outgas low molecular weight hydrocarbons which will react with other materials. Ester based lubricants also react similarly to hydrocarbons. Synthetic hydrocarbons will outgass less than mineral based lubricant but still can be considered reactive. Silicone lubricants have a strong desire to migrate and may adversely affect electrical conductivity of electrical contacts.

Low pour point and vapor pressure : PFPE, Z type, has a straight chain molecular structure which enables it to flow freely at very low temperature, (freezing point < -100°F). Also, it has a low vapor pressure at 20°C = < 4×10^{-13} torr. These two properties are the two most important properties for space application

Fire resistant: The PFPE oils and greases are not combustible under any circumstances making PFPEs safe to use in various critical applications, where fire resistance is a requirement.

Low surface tension: Low surface tension, 20 dyn/cm at 20°C, will ensure that oil will reach the narrow gaps in any machine it lubricates and also gives the highest oil to surface affinity, (see table II).

High Viscosity Index: A wide range of Kinematic Viscosity fluids with a high Viscosity Index, VI = 350, makes certain PFPE oils most suitable for applications that requires a small change in viscosity over a wide range of temperature (see Figure I).

Extreme Pressure: In the ASTM D-2596, 4-ball Weld Point Test, unadditised PFPE provides a pass result above 800kg. This property makes the PFPE a good lubricant in any application where a requirement exists for extreme pressure properties.

Safe operation: General chemical inertness and radiation resistance of the PFPE makes it the lubricant of choice in chemical and nuclear facilities.

Nontoxic and biologically inert: PFPE oil and grease applications are the safest among any other lubricant application. PFPE's relative non-toxicity and biological inertness makes it a preferred lubricant in the food and pharmaceutical industries.

Comparative Temperature Limits

Degrees Fahrenheit

-120 | -100 | -80 | -60 | -40 | -20 | 0 | 20 | 200 | 300 | 400 | 500 | 600 | 700

<---------- Mineral Oil ------------>

<-------------------- Polyglycol ---------------------->

<--------------- Synthetic Hydrocarbon ------------------>

<---------------------- Dibasic Acid Ester ---------------------->

<------------------------- Polyol Ester ------------------------------->

<------------------------------------- Perfluoropolyether ----------------------------->

Figure (II)

Comparative Surface tensions

Liquid in contact with air	Surface tension at 20°C dyne/cm
Perfluoropolyether	18 - 24
Ethyl Alcohol	22
Polyalphaolefin	25 - 29
Mineral oil	34
Water	73
Mercury	465

Table (II)

OTHER BENEFITS OF PFPE

- Wide temperature range.
- Low oil separation & outgassing/volatility.
- Long shelf life and storage stability.
- High oil VI and low pour point.
- High oxidative and thermal stability.

PFPE TYPICAL APPLICATIONS

- Aircraft instrument bearing grease.
- Air conditioning bearing and cabin pressurization valves on aircraft.
- Moderate to high radiation resistant lubricant applications.
- Mechanical components of cameras used in deep space.
- Astronaut space suite bearing and breathing apparatus lubricant.
- Robots in wafer handling in clean room environments.
- Scanning Electron Microscope (SEM) position table lubricant.
- Top coating lubricant on computer disc drive.
- Vacuum grease in semiconductor processing.
- Bearing in waste treatment facilities, & Anti-seize compounds.
- Automotive Breaking System (ABS).
- Impregnate for O-ring in pharmaceutical equipment.
- Pump seal and bearing lubricant in chlorine and strong oxidizer environments..

APPLYING PFPE

OIL FORM:

In closed and sealed applications, use oil for lubricating parts where a grease may be undesirable by means of the **Vacuum impregnating technique** as follow:

- Clean metal surface ultrasonically in a suitable solvent.
- Vacuum Bake @ minimum 29" Hg Vacuum and 120°F for 1 hour.
- Break vacuum to admit oil., Immerse bearing and O-ring.
- Vacuum bake again till bubbling ceases, release vacuum, remain 4 hours.
- Atmospheric pressure forces the impregnated oil into the bearing retainer.
- Remove parts from oil, drain, and centrifuge.

Impregnated part can weep oil over a long period of time in application

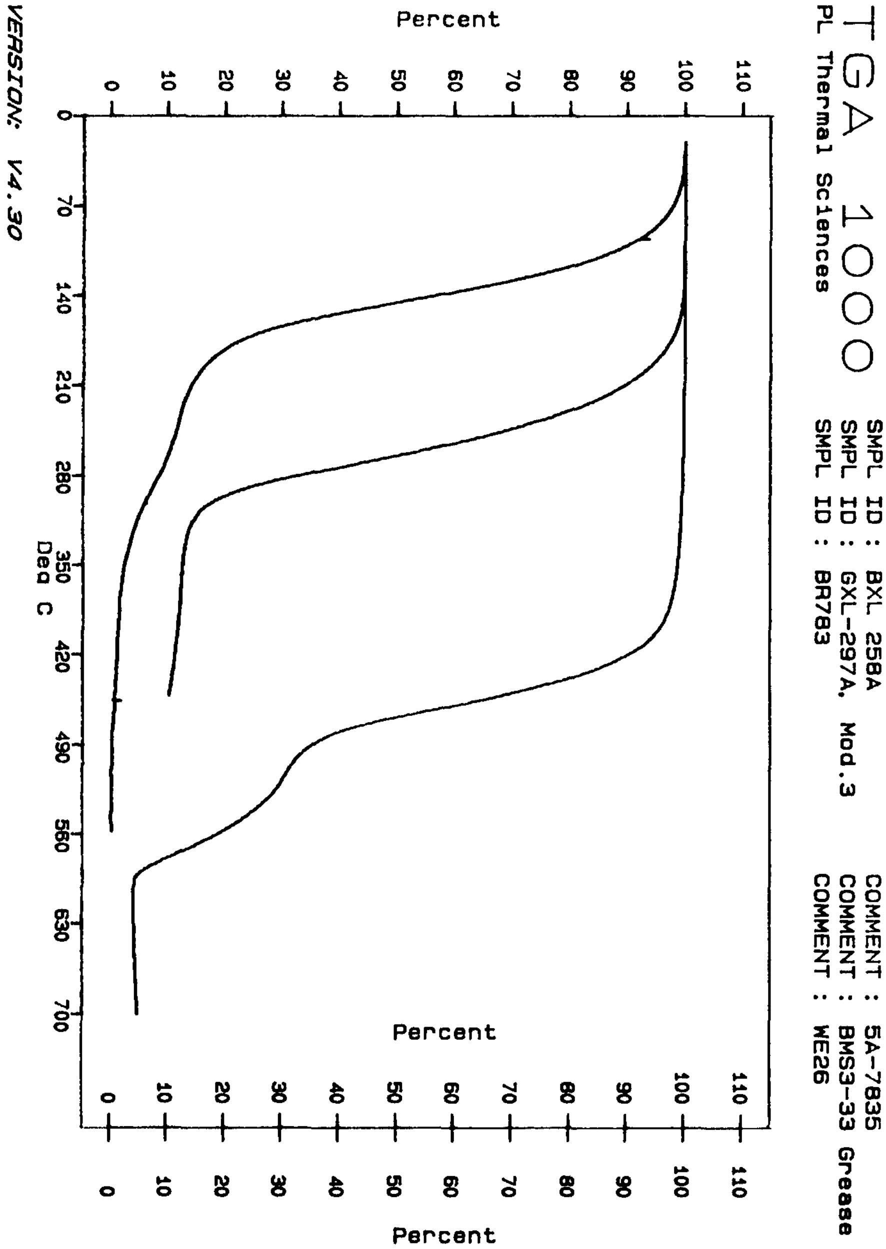
GREASE FORM:

In closed sealed/not sealed and in open bearing applications. In case there is not enough clearance to apply regular lubricant, OR concern about lubricant contamination for food industry use **Grease plating technique**, to apply thin uniform film of lubricant as follow:

- Grease + Volatile solvent (1:1) or other ratio, dip metal in mixture.
- Drain excess , heat to drive off solvent. Plate solution is stable for 6 hours
- By changing the ratio (1:1) we can control film thickness.

CLEANING PFPE:

Only fluorinated solvents can clean PFPE oils and greases. Hydocarbon solvents are not miscible with PFPE oils, so they can not clean it. Also PFPE oils has a very low surface tension than any hydrocarbon solvent, i.e., PFPE oil adheres strongly to the lubricated surface. More environmentally friendly solvents have been tested as replacements for Freon® 113. These solvents are short cabon chains, starting from five carbons saturated with fluorine atoms.



TGA 1000
PL Thermal Sciences
SMPL ID : BXL 258A
SMPL ID : GXL-297A, Mod.3
SMPL ID : BR783
COMMENT : 5A-7835
COMMENT : BMS3-33 Grease
COMMENT : WE26
Percent
Deg C
VERSION: V4.30

MANUFACTURING OF PFPE:

- Polymerization reaction starting with homomonomers, undergoes photooxidation, followed by a reduction reaction to yield a bi-functional chain. This can be followed by special thermal treatment to yield a mono-functional chain.
- Photochemical fluorination, then distillation to produce the straight chain. Or vacuum crack, then thermal fluorination and distillation to produce branched chain.

ADDITIVE COMPATIBILITY: PFPE oils and greases may contain additives to enhance their temperature/viscosity characteristics, extreme pressure properties, oxidation resistance, corrosion inhibition, and wear resistance. It is important to consider the effect of these additives in the clean room environment, i.e., molybdenum disulfide, a common extreme pressure additive, can create particles when used in a dry film polluting the air.

EXPERIMENT ON PFPE AND Li-COMPLEX GREASES

1) Low Temp. Torque per ASTM D-1478 @ -100°F		PFPE	Li-Complex
	Starting Torque	0.13 Nm	0.70 Nm
	Running Torque 1hr	0.048 Nm	0.10 Nm

2) Oil Separation Test per FED-STD-791, Method 321		200hr at 400°F	24hr at 400°F
	Oil Separation, %	14.18	21.75
	Oil Evaporation, %	0.77	9.32
	Total Weight Loss, %	14.95	31 .07

3) Low Temp. Torque per ASTM D-1478 @-100°F ,		with remaining grease after 2	
	Starting Torque	0.33 Nm	Frozen
	Running Torque 1hr	0.064 Nm	Frozen

DISCUSSION:

Step 1: The PFPE grease gives a very good torque results at -100°F when compared to a Li-complex grease using PAO/Ester base oil.

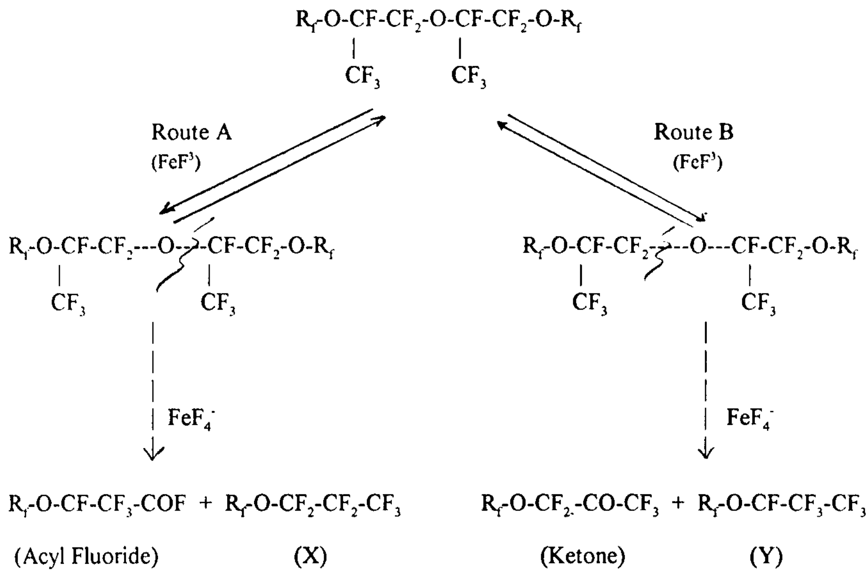
Step 2: The PFPE grease was tested for oil separation at 400°F for **200** hours and gave a better result than Li-Complex grease which was tested at 400°F for only **24** hours.

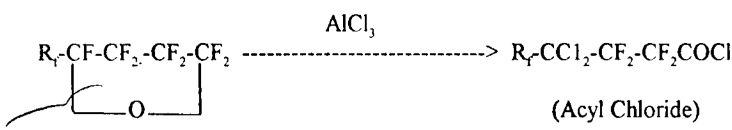
Step 3: The remaining PFPE grease from Step 2 gave almost the same result when tested for torque at -100°F, but the Li-Complex grease becomes frozen at -100°F.

The above unique performance of PFPE is due to it's excellant low temperature property, high thermal stability, and low oil separation tendency.

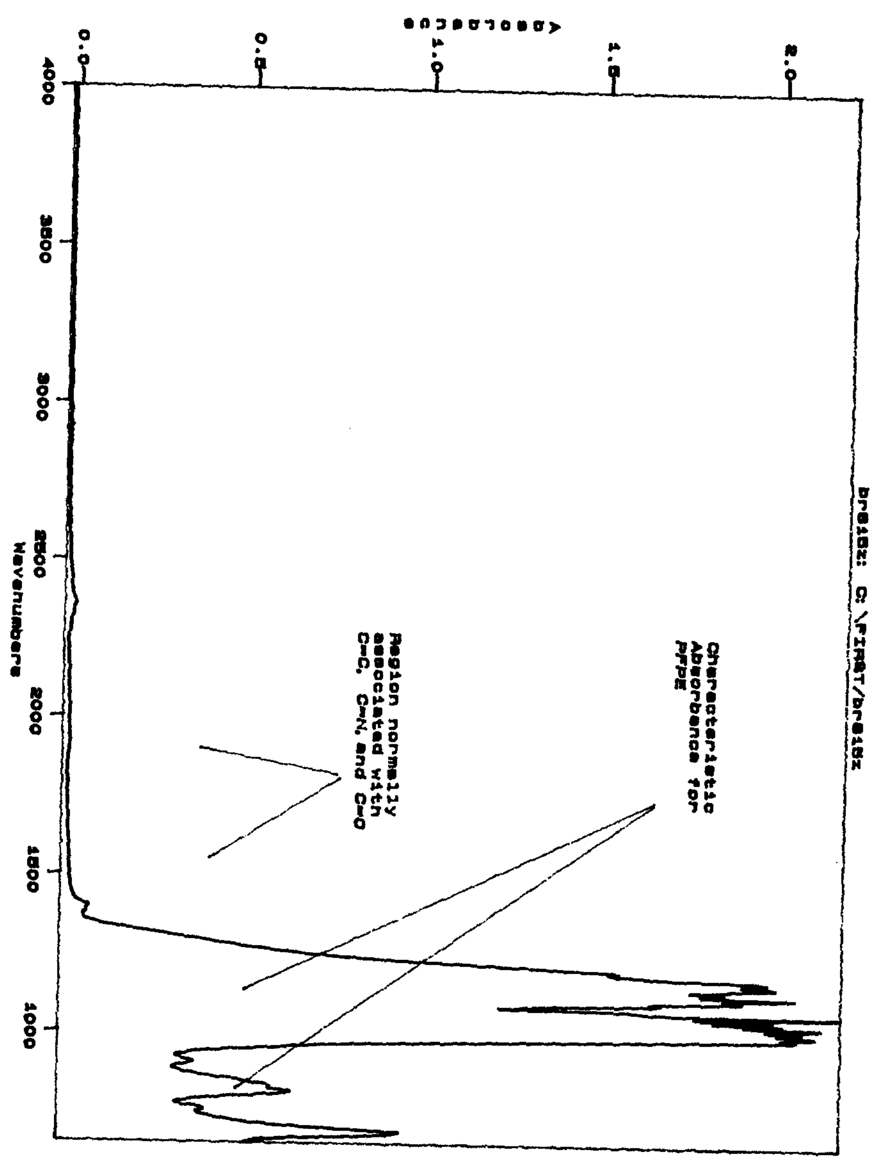
DEGRADATION OF PFPE BY FeF_3 AND $AlCl_3$

R_f and $R_{f'}$ = Perfluoropolyalkylether end groups of unspecified length.





The reaction products acyl fluoride and ketone are those expected for the catalyst-assisted cleavage of the etherate carbon-oxygen bond.


bre18z: C:\FIRST/bre18z
Absorbance
0.0
0.5
1.0
1.5
2.0
4000
3500
3000
2500
2000
1500
1000
Wavenumbers
Characteristic Absorbance for PFPE
Region normally associated with C=C, C=N, and C=O

NEW GENERATION HIGH PERFORMANCE GREASE (HYBRID)

Fluorinated greases are very high in performance which is required by some specific applications where the high price of PFPE can be justified. For other less severe applications PFPE lubricants are very expensive. There was a need for a lubricating grease at an affordable cost to fill the gap between the fluorinated and non-fluorinated greases.

Another reason for developing hybrid grease was its ability to emulsify water, unlike PFPE alone. In some applications, where the grease is exposed to water, then exposed to a cold environment, the water present with the grease becomes ice leading to an increase in the bearing torque. An example of the above condition is the wheel bearing of an airplane. Hybrid greases can contain the ice droplets within it's structure giving a torque result lower than PFPE alone in similar conditions.

Also in hybrid greases we can add non-fluorinated additives which will enhance the grease performance in certain areas. PFPE oils and greases are limited to the use of fluorinated additives due to miscibility/compatibility issue.

A new family of cost-effective greases combining fluorinated products with mineral or synthetic oils have been developed. These greases show long operating life at a temperature range from -50°C to 190°C. Above or below this temperature range, only fluorinated lubricants can be used.

Generally speaking, the major reason for non-fluorinated grease failure is the increased consistency due to oil loss which occurs due to oil evaporation, degradation and migration In hybrid greases, rate of oil loss due to evaporation and degradation may be reduced by the formation of fluorinated film which reduces friction. The migration rate could also be reduced by the formation of a lower surface energy fluorinated film.

Several lab developed samples are being tested in the lab and in the field to fully define the performance characteristics of these new hybrid greases. The ratio of the PFPE grease to the non-PFPE in these hybrid greases can vary depending on the desired grease properties and cost limitations. Also the chemical composition of hybrid grease can vary by choosing from a wide variety of PFPE greases and mixing it with different types of soap-thickened greases to meet the application requirements.

Suggested applications for the hybrid greases will include:
Automotive electric fans and clutches, steel mills, drilling plants, paper production, thermo insulating panel, electronics, wheel bearing of an airplane, and personal computer production.

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Intelligent Tool Condition Monitoring in milling operation

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Abstract: One of the most important features of the modern machining system in an "unmanned" factory is to change tools that have been subjected to wear and damage. An integrated system composed of multi-sensors, signal processing device and intelligent decision making plans is a necessary requirement for automatic manufacturing process. An intelligent tool wear monitoring system for milling operation will be introduced in this report. The system is equipped with four kinds of sensors, signal transforming and collecting apparatus and microcomputer. A unique ANN (artificial neural network) driven fuzzy pattern recognition algorithm has been developed from this research. It can fuse the information from multiple sensors and has strong learning and noise suppression ability. This lead to successful tool wear classification under a range of machining conditions.

Key Words: Condition monitoring; feature extraction; fuzzy pattern recognition; neural network; sensor fusion; tool wear classification.

1. Introduction: Metal cutting operation compounds a large percentage of the manufacturing activity. One of the most important objective of metal cutting research is to develop techniques that enable optimal utilization of machine tools, improved production efficiency, high machining accuracy and reduced machine downtime and tooling cost be possible. Tool condition monitoring is certainly the important monitoring requirement of unintended machining operations. It has been estimated that the development of methods to reliably detect the end of tool life could result in an increase of cutting speed from 10% to 50%, a decrease in cutting time, savings in tool changing time, and overall savings of 10 to 40% [1].

Many kind of sensing techniques have been used to monitor tool condition. An approach was developed for in-process monitoring tool wear in milling using frequency signatures of the cutting force [2]. The approach was based on the variations of the magnitude of cutting force harmonics along with flank wear. Some special parameters were used for detecting tool wear [3]. By processing the force signals, three characteristic parameters, the derivative of force wave form, power and coefficient of auto-correlation had been found to be relevant to tool wear. A relationship between the spindle motor current and the tool flank wear in turning operation was developed by Y. S. Liao [4]. It was found that the motor current increased nearly linearly from the beginning to the end of the tool's useful life if only one material was machined. Acoustic emission (AE) has been

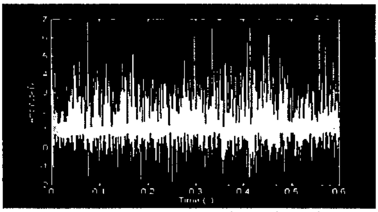
recognized as a promising means for on-line tool condition monitoring. The skew and kurtosis of the AE-RMS were related with the increase of the tool flank wear [5,6]. The dominant frequency components of AE signal are generally below 500 kHz. In this range the spectra amplitudes were found to increase with the accumulation of tool wear [7]. A scheme known as time domain averaging (TDA) was applied to process AE signal for on-line sensing of tool wear in face milling [8]. Experiment results showed that the mean AE-RMS energy had an increasing trend with the growth for natural insert wear. Statistical techniques were used to combine power spectrum estimates with higher-order spectrum (HOS) estimates to extract features [9]. Those features were applied to discriminate and classify vibration signals from new and slightly used drill bits in a drill wear study. The amount of tool wear in face milling was related to the change of the envelope (signal boundary) of the vibration signal [10]. Grieshaber et al [11] used spectral density and spectral area of vibration signal to identify tool wear in face milling.

It has been widely accepted now that under varying machining conditions, the information required to make reliable decisions on the tool wear state can hardly be available by using single sensor information. Sensor fusion is attractive since loss of sensitivity of one of the sensors can be compensated by other sensors. A discriminate function technique was used to combine force signal with acoustic emission information to monitor cutting tool condition [12]. Neural networks was proved to be suitable for integrating information from acoustic emission and cutting force sensors to predict tool wear in turning operation [13]. The sensor signal patterns and the tool wear states were successfully associated. Choi et al [14] developed a neural network-based real-time tool wear monitoring system. P.G.Li et al. [15] used fuzzy pattern recognition algorithm to monitor drilling tool wear. The thrust and torque are selected as the features relevant to drill wear and the relationship between these features and drill wear was found from fuzzy manipulation.

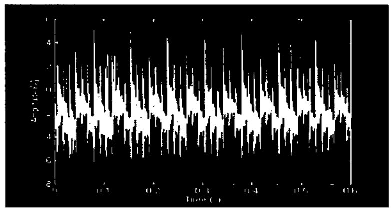
In this study, an ANN driven fuzzy pattern recognition algorithm was developed to accomplish multi-sensor information integration and tool wear states classification. By imitating the thinking and judging modes of human being, the technique shows some remarkable characteristics. Definite mathematical relations between tool wear states and sensor information are not necessarily needed. The effects caused by experimental noise can also be decreased greatly. The established monitoring system provided accurate and reliable tool wear classification results over a range of cutting conditions.

2. Tool condition monitoring system: The experiments were carried out on a Cincinnati Milacron Sabre 500 machining center. Like many other modern machine tools, it delivers a signal that is proportional to the power consumption rating of the spindle motor (up to 6.1 volts corresponding to 100% of the full power of the motor). A KISTLER 9257B force dynamometer was used to measure cutting forces, F_x, F_y, F_z, in three mutually perpendicular directions. The dynamometer has a measuring range of 5000 N in each direction, linearity of 1%, stiffness of 350 N/μm in the Z direction and 1000 N/μm in the X and Y directions and a resonant frequency of 4kHz. The acoustic emission (AE)

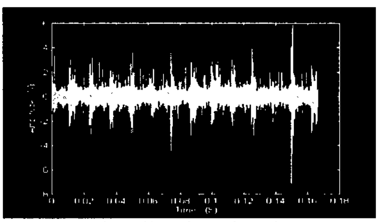
measuring apparatus includes an AE sensor and a signal processing device. The AE sensor has a measuring frequency range of 100kHz - 2MHz. An analogue module receives the input from the pre-amplifier and provides outputs of both amplified AE analogue signals and AE-RMS signals.



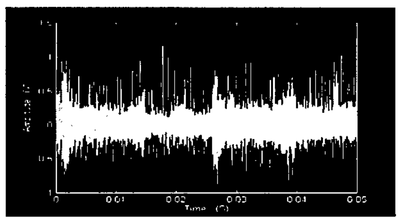
The power consumption signal



The cutting force signal



The vibration signal



The Acoustic emission signal

Fig.1 Tool condition monitoring sensor signals

An accelerometer was mounted in the feed direction. The sensor has a frequency response of 5 - 33 kHz, mounted resonant frequency 50 kHz. Fig.1 shows the power consumption, cutting force F_x (in the cutting direction), vibration and acoustic emission signals respectively. The tool wear monitoring system is composed of four types of sensors, signal amplifying and collecting devices and the main computer, as shown in Fig.2.

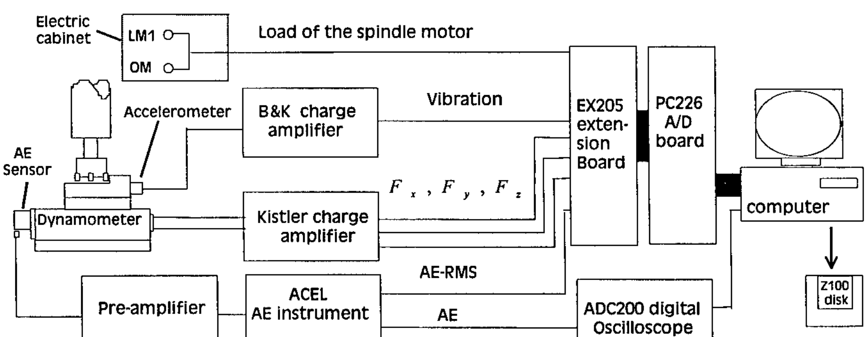
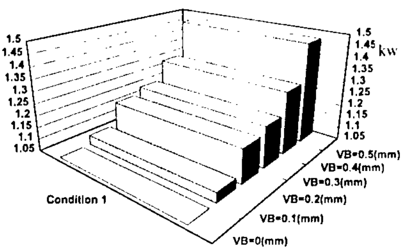


Fig.2 The tool condition monitoring system for milling operation

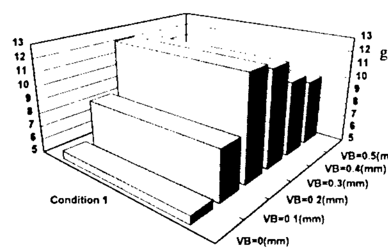
The dynamometer was fixed on the table of the machine with the workpiece mounted on the top of it. The accelerometer and the AE sensor were mounted on the side of the workpiece and the dynamometer respectively. The power consumption, vibration and cutting force signals were collected by the computer through an A/D board at 5 kHz, 300 kHz and 30 kHz respectively. The AE signal sampling was accomplished by using the digital oscilloscope at a frequency of 12 MHz.

3. ANN driven fuzzy pattern recognition: Tool condition monitoring is a pattern recognition process in which the characteristics of the tool to be monitored are compared with those of the standard models. The process is composed of the following parts: feature extraction, determination of the membership functions, calculation of the fuzzy distance, learning and tool wear classification.

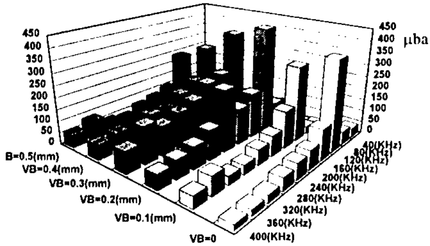
3.1 Feature extraction: Features extracted from the time domain and frequency domain for pattern recognition are as follows. Power consumption signal: mean value; AE-RMS signal: mean value, skew and kutorsis; Cutting force, AE and vibration: mean value, standard deviation and mean power in 10 frequency ranges within the working frequencies. As an example, Fig.3 shows several features (under cutting condition1*) in time and frequency domain. It can be seen that both the amplitude and the distribution pattern can represent the development of tool wear.



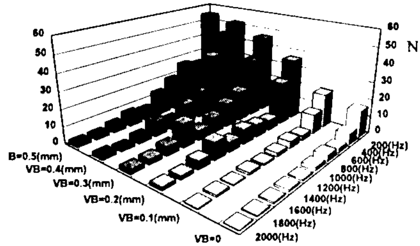
Mean value of the power consumption signal



Standard deviation of the vibration signal



Spectra of the AE signal



Spectra of cutting force (F_x) signal

Fig.3 Features extracted from different sensor signals

3.2 Determination of the membership functions of the features: The features of signals can reflect the tool wear states. For the standard model (groups of inserts with standard flank wear values), the j-th feature of the i-th model is a fuzzy set A_{ij}. Theoretical analysis and experimental results show that these features can be regarded as normal distribution fuzzy sets. The membership function of the fuzzy set A_{ij} can be represented as:

$$
\begin{aligned}
A_{ij}(x) &= e^{-\frac{(x-a_{ij})^2}{2\sigma_{ij}^2}} && a_{ij}-\sqrt{2}\sigma_{ij} < x < a_{ij} \\
&= 1 && a_{ij} \le x \le b_{ij} \qquad \text{.....................(1)} \\
&= e^{-\frac{(x-b_{ij})^2}{2\sigma_{ij}^2}} && b_{ij} < x < b_{ij}+\sqrt{2}\sigma_{ij} \\
&= 0 && \text{for other values of X}
\end{aligned}
$$

where a is the mean value and σ is the standard deviation. In order to determine the values of the coefficients in the formula, several groups of inserts possessing standard wear values were used in milling operations. K groups of specimens were drawn for the j-th feature, then for each group the mean value $\bar{x}_{ijt}$ and the standard deviation σ_{ijt} can be calculated (t=1,2,...,k). So a_{ij} and b_{ij} can be set as the maximum and minimum values of $\bar{x}_{ijt}$ and σ_{ij}^2 can take the mean value of σ_{ijt}^2. For a certain group of inserts with unknown wear value, its j-th feature can also be regarded as a normal distribution fuzzy set. It has following the membership function:

$$
\begin{aligned}
B_j(x) &= e^{-\frac{(x-\bar{x}_j)^2}{2\sigma_j^2}} && x_j-\sqrt{2}\sigma_j \le x \le x_j+\sqrt{2}\sigma_j \\
&= 0 && \text{for all others} \qquad \text{.........................(2)}
\end{aligned}
$$

3.3 The approaching degree: One of the quantitative indexes that represent the fuzzy distance between two fuzzy sets (A and B) is known as the approaching degree. Assume that $\Im$ (X) is the fuzzy power set of a universal set X and the map, N: $\Im(X) \times \Im(X) \rightarrow [0,1]$, satisfies

(1). $\forall A \in \Im(X)$, $N(A,A)=1$

(2). $\forall A,B \in \Im(X)$, $N(A,B)=N(B,A)$

(3). If $A,B,C \in \Im(X)$ satisfies

$$|A(x)-C(x)| \ge |A(x)-B(x)| \;\; (\forall x \in X) \;\; \text{then} \;\; N(A,C) \le N(A,B)$$

so the map N is the approaching degree in $\Im(X)$ and $N(A,B)$ is called the approaching degree of A and B. It can be calculated by using different methods. Here the inner and outer products are used. Assume that $A,B \in \Im(X)$, so $A \bullet B = \vee\{A(x) \wedge B(x): x \in X\}$ is

defined as the inner product of A and B and $A \oplus B = \wedge\{A(x) \vee B(x): x \in X\}$ is defined as the outer product of A and B. Finally, in the map N: $\Im(X) \times \Im(X) \rightarrow [0, 1]$, $N(A, B)$ is the approaching degree of A and B.

$$N(A,B) = (A \bullet B) \wedge (A \oplus B)^c \qquad \text{.......................(3)}$$

3.4 The ANN driven fuzzy pattern recognition algorithm: Using the conventional fuzzy pattern recognition technique, the fuzzy distances (such as approaching degree) between corresponding features of the object to be recognized and the models are first calculated, combining these distances can determine the fuzzy distance between the object and different models. The object should be classified to one of the models that have the shortest fuzzy distance (or highest approaching degree) with it. Because most features have vague boundaries so using fuzzy membership function to represent their characteristics and fuzzy distance to describe the similarity of corresponding features are quite appropriate. Fuzzy pattern recognition techniques are thus quite reliable and robust. They can be further improved by developing a method that can assign suitable weights to all the features to reflect the specific influences of different features in the pattern recognition process. For solving this problem, an advanced ANN driven fuzzy pattern recognition algorithm is developed from this study.

Artificial neural networks (ANNs) have the ability to classify inputs. The weights between neurons are adjusted automatically in the learning process to minimize the difference between the desired and actual outputs. ANN can continuously classify and also update classifications. In this study, ANN is connected with fuzzy logic technique to establish an ANN driven fuzzy pattern recognition algorithm. It's principle is shown in Fig. 4.

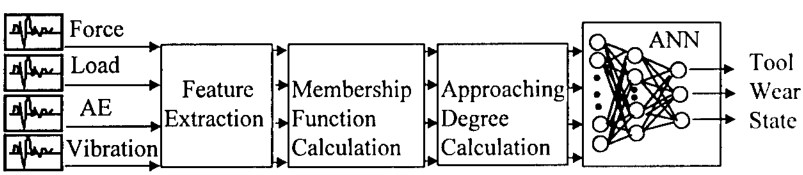


Fig.4 The ANN driven fuzzy pattern recognition algorithm

Here a back propagation ANN is used to carry out tool wear classification. The approaching degree calculation results are the input of the ANN. The associated weights can be updated as: $w_i(new) = w_i(old) + \alpha \delta x_i$. Here α, δ, x_i are learning constant, associated error measure and input to the i-th neuron. In this updating process, the ANN recognizes the patterns of the features corresponding to certain tool wear state. So in practical machining process, the feature pattern can be accurately classified to that of one of the models. In fact ANN assigns each feature a proper synthesized weight and the output of the ANN are weighted approaching degrees. This enables the tool wear

classification process be more reliable. Fig.5 shows the calculation process of tool wear states classification.

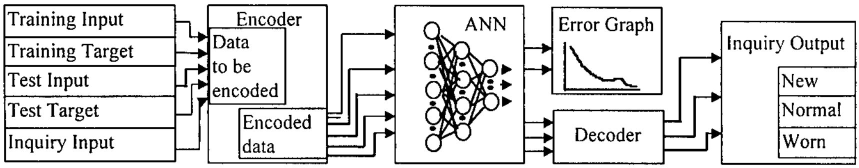


Fig.5 The tool wear states classification process

3.5 Learning: Six standard tool wear values were selected as the models for the future pattern recognition, ranging from new to severe wear where the width of the flank wear area increased from 0 to 0.5 mm in steps of 0.1 mm. Three standard flank wear value, 0, 0.2 mm and 0.5 mm are used to represent new tool, normal tool and worn tool. For each tool with the standard wear value, the membership functions of all its features can be calculated and then stored in a library in the computer. As an example, Table 1 shows the coefficients of some of the features (mean power in ten frequency ranges) of cutting force F_x for three standard models under cutting condition1*, then the membership functions of those features can be determined by using formula (1). These are called the main membership functions

Table 1 Coefficients of the membership function of features of F_x

VB.(mm)=	0			0.2			0.5		
FREQUENCY (kHz)	a_{ij}	b_{ij}	σ_{ij}	a_{ij}	b_{ij}	σ_{ij}	a_{ij}	b_{ij}	σ_{ij}
0~0.2	0.21	0.23	0.007	0.529	0.567	0.017	0.98	0.99	0.082
0.2~0.4	0.152	0.215	0.025	0.371	0.542	0.072	0.723	0.952	0.176
0.4~0.6	0.023	0.055	0.009	0.163	0.306	0.063	0.266	0.367	0.045
0.6~0.8	0.076	0.083	0.011	0.076	0.124	0.023	0.163	0.233	0.037
0.8~1	0.043	0.086	0.016	0.092	0.146	0.063	0.166	0.231	0.036
1~1.2	0.013	0.018	0.003	0.072	0.135	0.031	0.094	0.202	0.053
1.2~1.4	0.011	0.018	0.001	0.076	0.103	0.014	0.046	0.125	0.035
1.4~1.6	0.011	0.017	0.006	0.156	0.216	0.025	0.132	0.263	0.066
1.6~1.8	0.012	0.034	0.011	0.078	0.108	0.017	0.033	0.117	0.035
1.8~2	0.013	0.035	0.009	0.032	0.038	0.027	0.023	0.062	0.017

The training process of the ANN is as the following: by using formula (2) 20 groups of membership functions of all the features for each model can be determined. These are called sub-membership functions. They can represent many sub-models that also have standard tool wear values. Then using equation (3) can decide the approaching degrees between the corresponding features of these sub-models and six models (from new to worn). The results can be used as the training inputs of the ANN. The training targets can be determined like this: the weighted approaching degrees between each model and its own sub-models should be 1 and weighted approaching degrees between a model and other model's sub-models can be calculated by decreasing the value from 1 to zero

linearly. After the training the constructed frame and associated weights of the ANN can reflect the distinct importance of each individual feature for each model under specific cutting conditions. So the tool wear classification results can be reliable and accurate. The determination of the membership functions of all the features for each model and the construction of ANNs for classification mark the end of the learning stage.

3.6 Tool wear classification: In the practical tool condition monitoring process, the tool with unknown wear value is the object and it will be recognized as "new tool", "normal tool" or "worn tool". By using equation (2), the membership functions of all the features of the object can be determined. As an example, Table 2 lists the coefficients of the membership function for the frequency components of the cutting force F_x under cutting condition1*. The flank wear value of this group of inserts is 0.25 mm.

Table 2 Coefficients of the membership function of cutting force F_x

Frequency (kHz)	0~0.2	0.2~0.4	0.4~0.6	0.6~0.8	0.8~1.0	1.0~1.2	1.2~1.4	1.4~1.6	1.6~1.8	1.8~2.0
$\overline{x}_i$	0.561	0.411	0.203	0.088	0.125	0.098	0.079	0.158	0.076	0.035
σ_i	0.025	0.092	0.046	0.029	0.033	0.012	0.024	0.016	0.005	0.006

The approaching degrees of the corresponding features of the standard model and the object to be recognized can be calculated by using equation (3). As an example, Table 3 shows the approaching degrees between part of corresponding features (10 frequency components of the cutting force F_x under cutting condition1*) of a group of inserts (VB=0.25 mm) and three standard models

Table 3 Part of the approaching degree calculating results

Frequency (kHz) / Models	0~0.2	0.2~0.4	0.4~0.6	0.6~0.8	0.8~1.0	1.0~1.2	1.2~1.4	1.4~1.6	1.6~1.8	1.8~2.0
VB=0 (mm)	0	0.21	0	0.57	0.47	0.49	0.16	0	0	0.71
VB=0.2(mm)	0.75	0.86	1	0.79	0.93	1	1	0.66	1	0.86
VB=0.5 (mm)	0	0.26	0.49	0.35	0.57	0.52	0.5	0.32	0.53	0.63

The approaching degrees between the corresponding features of the object and different models can be the inquiry input of the ANN. One of a pre-trained ANN is then chosen to calculate the weighted approaching degree between the object and a model under a specific cutting condition. Finally the tool wear state should be classified to the model that has the highest weighted approaching degree with the tool being monitored. In a verifying experiment, fifteen tools with unknown flank wear value were used in milling operations under cutting condition1*. Fig.6 shows the classification results. It can be seen that all the tools were classified correctly with the confidence of higher than 80%. Experiments under other two cutting conditions showed the similar results.

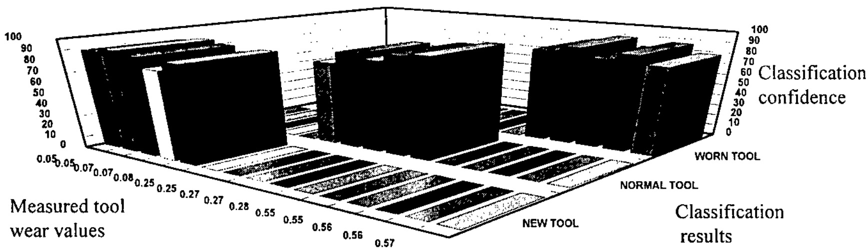


Fig.6 Tool wear states classification results.

4. Conclusions: A methodology has been developed for on-line tool condition monitoring in milling using four kinds of transducers and tool wear relevant features are extracted from the time and frequency domains. Tool wear classification is realized by applying ANN driven fuzzy pattern recognition algorithm. On the basis of this investigation, the following conclusions can be made.

(1) Power consumption, vibration, AE and cutting force sensors are applicable for monitoring tool wear in milling operations. The healthy signals picked up by these sensors within different working frequency ranges describe tool condition comprehensively.

(2) Many features extracted from time and frequency domains are found to be strongly relevant to the changes of tool wear state. This makes accurate and reliable pattern recognition possible.

(3) The combination of ANN and fuzzy logic technique integrates the strong learning and classification ability of the former and the superb flexibility of the latter to express the distribution characteristics of signal features with vague boundaries and the fuzzy distances between them. This methodology indirectly solves the weight assignment problem of the conventional fuzzy pattern recognition system and let it have greater representative power, higher training speed and be more robust.

(4) The ANN driven fuzzy pattern recognition algorithm is effective and suitable for tool wear monitoring. It can carry out the integration and fusion of multi-sensor information. Fuzzy approaching degree can measure the similarity between signal features accurately and the ANN successfully accomplishes the tool wear states classification.

(5). Armed with the advanced pattern recognition methodology, the established intelligent tool condition monitoring system has the advantages of being suitable for different machining environments, robust to noise and tolerant to faults. Accurate tool wear classification can be achieved over a range of machining conditions.

Future work will attempt to identify data processing methods that produce feature vectors describing tool condition more accurately. The ANN driven fuzzy pattern recognition technique will be improved by the application of other forms of fuzzy distances, advanced fuzzy clustering techniques and the optimization of the ANN structure.

* Cutting condition1: cutting speed - 600 rev/min, feed rate - 1 mm/rev, cutting depth - 0.6 mm, workpiece material - EN1A, cutting inserts - Stellram SDHT1204 AE TN-42.

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The Dielectric Constant of Lubrication Oils

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Abstract: The values of the dielectric constant of simple molecules is discussed first, along with the relationship between the dielectric constant and other physical properties such as boiling point, melting point and refractive index. The Debye equation shows the relationship of dielectric constant with the polarizability and dipole moment of materials. The interpretation of the Debye equation as it applies to lubrication oils is considered. The effect of base oil (paraffinic versus napthenic) and additives on the dielectric constant of oils is included in this paper. The temperature and electric field frequency dependence of dielectric constant on lubrication oils is discussed.

Key Words: Additives; Debye equation; dielectric constant; lubricant properties; temperature dependence of dielectric constant.

Introduction: Several companies such as Computational Systems Inc. (Knoxville, TN), Kavlico (Moorpark, CA) and Control Devices (Standish, ME) manufacture a capacitance sensor for measuring oil quality. The capacitance of the oil sensor is directly proportional to a property of the oil called a dielectric constant. This paper discusses the dielectric constant of materials, the Debye equation and its application to lubrication oils.

What is a dielectric constant? A dielectric constant is a fundamental property of a material, along with: boiling point, melting point, viscosity, and refractive index. A dielectric constant measures the interaction of an oscillating electric field (that is an electric field that oscillates between positive and negative values at a certain AC frequency) with a molecule. A dielectric constant is a dimensionless number. In pure simple compounds, the values of boiling point, melting point, viscosity, and refractive index are strongly influenced by their dielectric constant. We can compare three simple molecules (of approximately the same molecular weight) like lithium fluoride (LiF), ethane (C_2H_6), and nitrogen (N_2) with various physical properties:

Table I: Dielectric constant and physical properties of simple compounds [1]

Property	LiF	C_2H_6	N_2
Dielectric constant	9.00 (5 ^{0}C)	1.9356 (-178 ^{0}C)	1.4680 (-210 ^{0}C)
Melting Point ^{0}C	845	- 172	-210
Boiling Point ^{0}C	1676	-88	-196
Molecular weight g/mole	26	30	28

Table I shows that there is a relative simple relationship between dielectric constant and boiling and melting points for compounds of approximately the same molecular weight. Namely as the dielectric constant increases, so does the melting and boiling point of simple molecules. Later we will extrapolate these concepts when going to large molecules like lubrication oils. The viscosity of a substance is related to dielectric constant by way of its boiling point. The boiling point of most substances (including lubrication oils) occurs when the viscosity is within 0.4 to 1.4 centistoke. In the case of boiling, it is heat that supplies the energy to overcome the forces between molecules and permits expansion to a gas. The dielectric constant is (partly) a measure of the forces between molecules which must be overcome by heat. In summary, a dielectric constant measures the forces between molecules of a substance. This is relevant to oils where the interaction between molecules is weak (which gives it lubricating properties) and the dielectric constant of oils is relatively small (because the interaction between molecules is small). We will discuss the relationship between dielectric constant and refractive index later.

Table II: Dielectric constant of common materials [1]

Vacuum	1 (exactly)
Metals	Infinite
Gases	1.00xx (at one atmosphere)
Water	87.9 (0 C) to 55.5 (100 C)
Hexane	1.8865 (20 C)
Benzene	2.285 (20 C)
Lubrication oils	2.1 to 2.8 (room temperature)

The dielectric constant of a vacuum is exactly one by definition, whereas metals have an infinite dielectric constant because they are conductors (Table II). The density of gases is about one thousandth the density of solids and liquids and therefore have relatively small dielectric constants (1.00xx). Water has an anomalously large and temperature dependent dielectric constant. Hexane is a simple six carbon paraffinic type compound and has a lower dielectric constant than benzene which is also a simple six carbon aromatic (napthenic) compound. Hydrocarbon lubrication oils have a dielectric constant from 2.1 to 2.8, which depends on the viscosity of the oil, the paraffinic/napthenic content, and additive package.

A molecule contains a positive charge (the nucleus which is relatively massive) and negative electrons which surround the nucleus and are involved in forming chemical bonds. The negative electrons are moving at near the speed of light around (or between) atoms. When a dielectric constant is quoted for a material, the value depends on the electric field frequency and the temperature of the substance. The values of dielectric constant reported in Tables I and II are extrapolated to a zero frequency electric field.

A dielectric constant (also known as permittivity) represents the sum of two different component properties of materials (including lubrication oils): the polarizability, and the dipole moment.

Polarizability is a fundamental property of all atoms and molecules and therefore all material objects. Polarizability measures the interaction of the electrons in a molecule with an electric field. All atoms and molecules are composed of a positively charged nucleus surrounded by negatively charged electrons. Imagine a single hydrogen atom (one proton and one electron) between two parallel plates. If an electric potential is created between the plates, the nucleus is displaced towards the negative plate and the electron is displaced towards the positive plate, in other words the atom (or molecule) is polarized. This displacement is proportional to the electric field until (at sufficiently high voltages) dielectric breakdown occurs. Dielectric breakdown occurs when electrons (rather than electric fields) travel between the capacitor plates. The magnitude of the potential difference between the plates when dielectric breakdown occurs is called the dielectric strength. The magnitude of the proportionality (α) between the induced dipole and electric field (before dielectric breakdown occurs) is called polarizability [2].

$$\mu_{\text{Induced}} = \alpha E \qquad \textbf{1}$$

Where μ_{induced} represents the induced dipole moment, α is the polarizability and E is the electric field. The polarizability term (α) has dimensions of cm^3. The electrons in aromatic compounds (napthenic) are more polarizable than the electrons in paraffinic compounds. Therefore napthenic oils should have larger dielectric constant than paraffins.

A dipole moment measures the center of gravity of the positive and negative charges in a molecule. If these two centers do not coincide, then the molecule is electrically unsymmetrical and has a net polarity and therefore a permanent dipole. In a compound like water (H_2O), the oxygen atom shares electrons with the hydrogen atom. However, the oxygen atom holds the negative electrons more strongly than the hydrogen atoms. Thus, the oxygen atom has a more negative charge and the hydrogen atoms are more positive, in other words the molecule is polar. The dipole moment, μ, is defined as the magnitude of a unit charge e (in esu) times the distance r between charges (in cm), and it is expressed in Debyes (1 Debye = 10^{-18} esu-cm). Molecules with a dipole moment have two physically separated charge centers. In an electric field the charge centers align themselves to oppose the field. If the electric field oscillates, the entire molecule has to

rotate. In microwave cooking, the water molecules are rotating at such a frequency (10^9 Hz) that they dissipate energy in the form of friction, causing the heating. Almost all materials (including lubrication oils) show a decrease in dielectric constant at higher electric field frequencies. At higher electric field frequencies there is not sufficient time for the molecule to rotate, and therefore only the polarizability term contributes to the dielectric constant.

The Debye equation: The dielectric constant (ϵ) is related to the polarizability (α) and the dipole moment (μ) by the Debye equation. The relationship is rather messy but we can break it down into simpler parts.

$$(\epsilon - 1)/(\epsilon + 2) = (\alpha + \mu^2/3kT)(L\rho/3MW) \qquad \mathbf{2}$$

ϵ = permittivity (dielectric constant) of oil
α = polarizability of oil
μ = dipole moment of oil
k = Boltzman constant = $1.31*10^{-23}$ joules/degree Kelvin
T = temperature degrees Kelvin = 273 + degrees centigrade
L = Avogadro number = $6.02*10^{23}$ molecules of oil/mole
ρ = density of oil = grams/cm^3
MW = molecular weight of oil = grams/mole

The term ($L\rho/3MW$) represents the volume of a single molecule. The term kT represents the amount of thermal energy available (thermal energy gives molecules random motion). Thus, the dielectric constant is a direct result of the polarizability (α) and dipole moment (μ) of a molecule. Base oil makes only a small contribution to the dipole moment term in the Debye equation, and therefore shows a relatively small change in dielectric constant.

Almost all additives (antiwear compounds, antioxidants, detergents, dispersants etc) contain compounds with dipole moments. This is the reason why additives increase the dielectric constant of lubrication oils. Moreover, as the Debye equation indicates, the dipole moment contribution to the dielectric constant shows a direct inverse temperature relationship. Therefore, additives show direct temperature dependence, whereas the base oil does not.

The Debye equation works well with gases because the large distance between molecules causes weak interaction between dipoles. In solids, because of constraints imposed by the crystal structure, the Debye equation gives useful information. In solids the crystal structure 'freezes' the dipoles in a fixed geometric orientation, and direct solution of the Debye equation is possible. In liquids, thermal motion is continuously changing the orientation of dipoles

The polarizability term at optical frequencies can be determined simply by measuring the refractive index of the oil sample. The equation for determining the

polarizability from refractive index is:

$$\alpha = (n^2 - 1)/(n^2 + 2)^* \, (L\rho/3MW) \qquad \mathbf{3}$$

Where n is the refractive index. As can be seen, this equation is similar to the Debye equation. Thus the polarizability term in the Debye equation for dielectric constant is related to the refractive index of the oil.

The Debye equation works well with gases because they are dilute and the distance between molecules is large. The large intermolecular distance implies that there is no dipole-dipole interaction. The Debye equation works only approximately in solids because they have a rigid crystal structure that restricts the molecular orientation. Nevertheless, there is an enormous amount of literature on the dielectric behavior of plastics both as a function of frequency and temperature [3]. Changes in dielectric behavior of plastics are usually associated with localized motion in the polymer systems, that is, side-group rotation, short order motion in the main chain, and so-on. Thus, orientation and movement of dipoles present in the system cause dielectric changes in solids. The Debye equation is complicated in liquids because of dipole-dipole interactions produced by polar materials while thermal motion is continuously reorienting the molecular dipoles.

Lubrication oils: Although the Debye equation does not work exactly for liquids, it is still useful for interpreting the dielectric behavior of lubrication oils. First, the oil base stock contains no polar materials and therefore does not have a dipole moment (μ) contribution. That is, the oil base stock only contains a polarizability (α) term in the Debye equation, which is related to the refractive index. The polarizability of aromatic (napthenic) compounds is higher than paraffinic because of the delocalized electrons in the aromatic nucleus are more polarizable [4]. Since there is no dipole moment contribution in the oil base stock, there is no direct temperature dependence to the dielectric constant. However, the dielectric constant in the Debye equation contains a term for the density of the oil, and therefore should show temperature dependence due to changes in the density of the oil with temperature. To a first approximation, the temperature dependence of the dielectric constant of the oil base stock is affected by changes in density of the oil. The change in density with temperature varies from 0.716 to 0.658 mg/ml K for oils with 40 C viscosity of 10 and 1500 cSt respectively [5]. As a matter of fact, the dielectric constant of hydrocarbon fuels (which contain smaller carbon chains than lubrication oils) correlates with fuel density, within an accuracy of 2%, according to the equation

$$\epsilon = 0.001667\rho + 0.785 \qquad \mathbf{4}$$

Where ρ is the fuel density in kg/m^3 at the temperature of interest [5]. Typical densities of lubrication oils vary from 0.829 to 0.908 g/ml with 40 C viscosity of 10 and 1500 cSt respectively.

The temperature dependence of dielectric constant of oils shows a hysteresis using several different dielectric sensors. Figure 1 shows the temperature dependence of the dielectric constant of pure mineral oil (no additives) using a sensor manufactured by Kavlico. This sensor operates at an electric field frequency of about 100 kHz. The figure shows that there is a slight difference in dielectric constant of the oil at a particular temperature during warm up and cool down. This hysteresis effect was found to occur with all oils tested. The effect could be caused by out gassing of water (or dissolved gases) during heating and cooling. Other explanations include electrical effects occurring in the sensor during warming and cooling or molecular relaxation in the fluid. The precise shape and value of the dielectric vs. temperature curve for any oil is probably dependent on the oil base stock and additive package present.

The dielectric constant of almost all additives (especially those containing nitrogen or oxygen atoms) are larger (often 6 to 10) than the base oils stock (2.1 to 2.4). These additives have a dipole moment and should show a different temperature dependence on the dielectric constant than oil base stock. Common additives used in lubrication oils are compounds belonging to the zinc dialkly dithiophosphates (ZDDP) used in many formulations. Figure 2 shows the dielectric constant vs. temperature during cool down of mineral oil with 1700 ppm of ZDDP. The ZDDP used in this experiment had a dielectric constant of 3.92 at room temperature. The figure shows an increase in dielectric constant at low temperature due to the presence of ZDDP, while the dielectric constant at higher temperature is approximately the same as neat mineral oil.

Synthetic oils such as polyol esters (POE), polyakyleneglycols (PAG), and phosphate esters have higher dielectric constants. For synthetic oils the value of the dielectric constant depends to a large degree on the oxygen content.

Experiments have shown that the dielectric constant of used lubrication oils is higher than unused oils. The exact increase depends on the amount of water and other contaminants present in the system as well as the amount of oxidation/degradation products present in the oil. Further tests are required to quantify this increase.

Conclusions: The accurate measurement of dielectric constant is an excellent method for measuring oil quality. It is believed that measuring the temperature dependence of the dielectric constant will provide a useful real-time method of measuring oil quality in operating systems.

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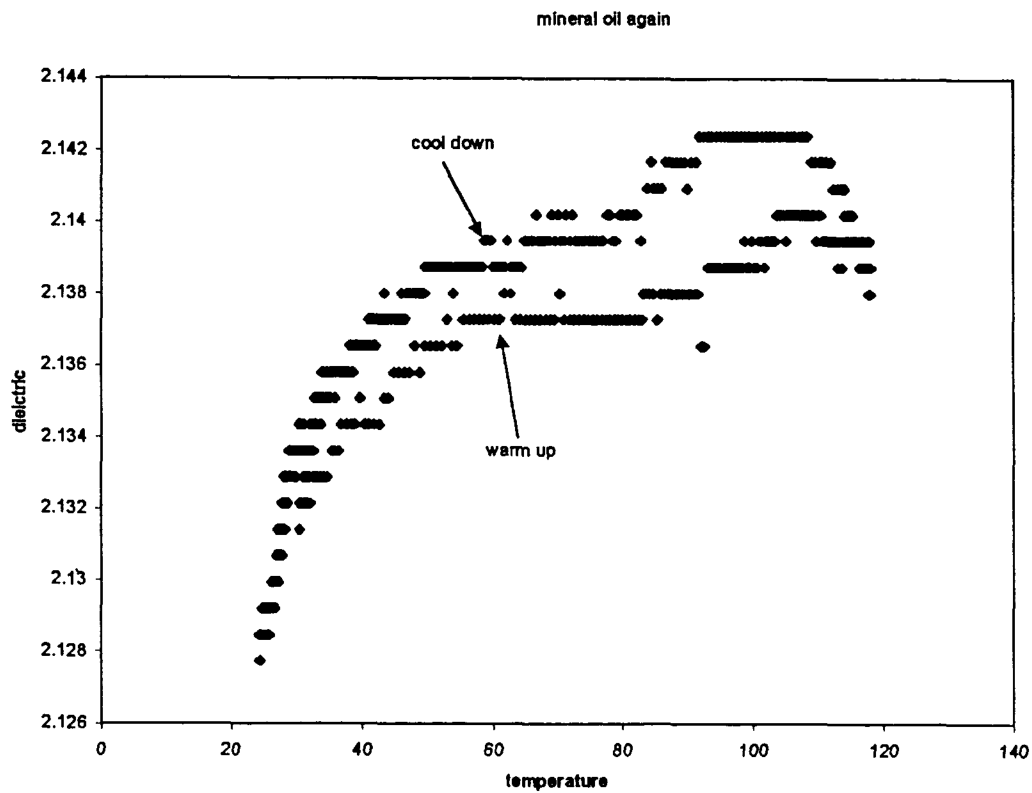

Figure 1: Temperature dependence of dielectric constant of mineral oil (Kavlico sensor)

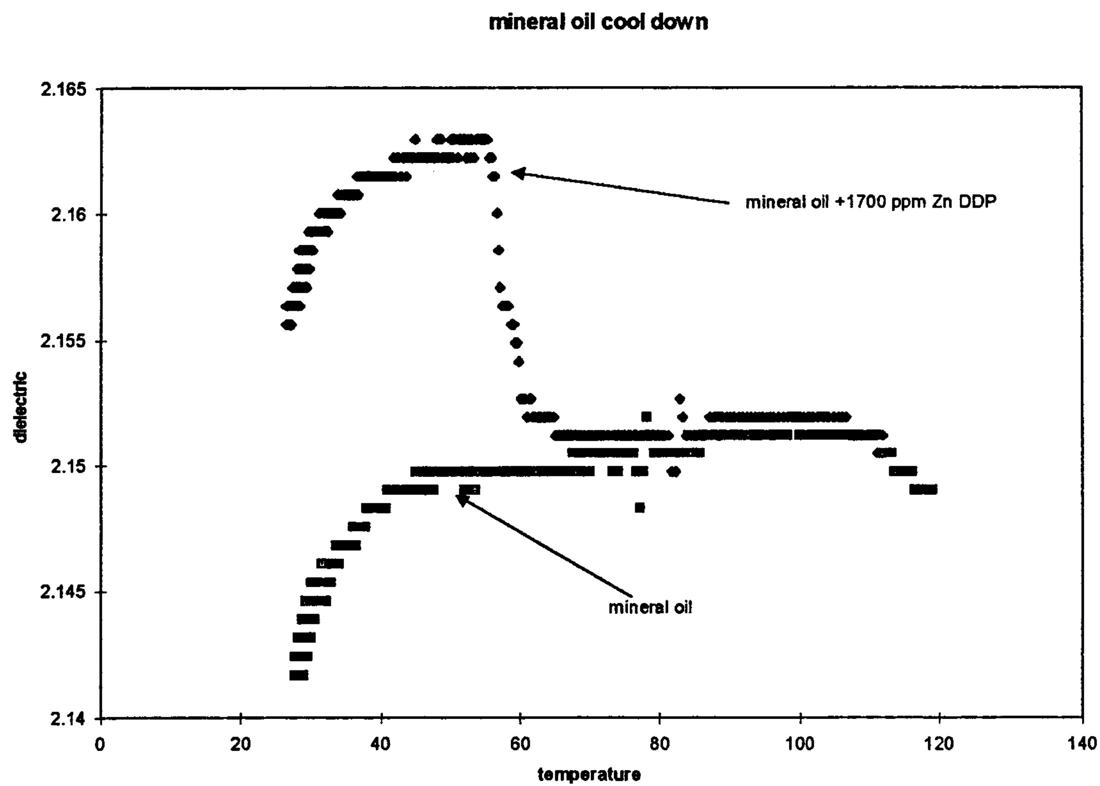

Figure 2: Temperature dependence of dielectric constant of mineral oil with 1700 ppm ZDDP (cool down)

Automated Machinery Health Monitoring Using Stress Wave Analysis & Artificial Intelligence

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Abstract: This paper describes the current state of development of a prototype mechanical diagnostic system being developed for the U.S. Army, for application to helicopter drive train components. The system will detect structure borne, high frequency acoustic data, and process it with feature extraction and polynomial network artificial intelligence software. Data for network training and evaluation has been acquired from both healthy and discrepant components, operated over a full range of loads, in a test cell.

Stress Wave Analysis (SWAN™) is a high frequency acoustic sensing and signal conditioning technology, which provides an analog signal that is a time history of friction and shock events in a machine. This "Stress Wave Pulse Train" (SWPT) is independent of background levels of vibration and audible noise. The SWPT is digitized and used to compute a set features that characterize the "friction signature". Fault Detection Networks of polynomial equations are used to automatically classify SWPT features as being representative of either healthy or discrepant mechanical components. The application of these techniques for automatic classification of friction signatures advances current technology to achieve real time diagnostic capability ***at all flight power levels***.

Keywords: Health Monitoring; Stress Wave Analysis (SWAN); Artificial Intelligence; Predictive Maintenance; Poylnomial Network Modeling; Structure-borne Ultrasound;

System Description: The Distributed Stress Wave Analysis (DSWAN) system consists of stress wave sensors, interconnect cables, and three types of modules: Distributed Processing Units (DPU's), a Maintenance Advisory Panel (MAP), and a LapTop Computer (LTC). The sensors, DPUs, and MAP are airborne components of the system. The LTC is ground based, and is not required for in-flight autonomous operation of the DSWAN airborne components.

Each DPU scans up to 8 sensor locations, extracts the friction and shock signal from broadband noise, and uses Fault Detection Network (FDN) software to detect abnormal friction/shock signatures from the monitored components. The monitored components

include all the H-60 primary drive train elements except the engines. Although up to four DPU's can be connected to one MAP, only two will be required to monitor the 15 H-60 drive train sensors. The DPU also contains Diagnostic & Prognostic Network (DPN) software for Sensor Validation Networks (SVN's), Regime Recognition Networks (RRN's), and self test.

When a DPU detects a potential problem, it turns on an associated indicator on the MAP. The LTC can then be used, during a post flight inspection, to download, analyze, and display, detected and forecasted problems. The LTC can also be used to upload new software to the DPU memory, or to reprogram a DPU for use with a different set of sensors.

Data Base Description: The data employed in the development and evaluation of the various types of DPN's was acquired from the U. S. Navy's H-60 test cell, located at the Naval Air warfare Center in Trenton, NJ. This facility consists of an entire shipset of H-60 helicopter drive train components, (including turboshaft engines) with associated loading mechanisms, to exercise the drive train over a full range of operating loads. Over a period of 32 months, from August of 1994 through April of 1997, baseline and seeded fault drive train components were tested. High frequency acoustic (stress wave) data was acquired from 15 sensor locations (listed in Table I) using a DME SWAN 3000 data acquisition system and a TEAC Digital AudioTape (DAT) recorder. The PC based SWAN 3000 scanned the 15 sensor locations, then filtered and demodulated the high frequency acoustic data to provide a demodulated Stress Wave Pulse Train (SWPT) for recording on the DAT.

Case Descriptions: The following paragraphs describe the baseline and seeded fault ("CASE") test configurations used in training and evaluating DPN's from the main transmission assembly data base.

Baseline MM02: This was one Main Module with non discrepant components and Input Modules, but it was tested first in August of 1994, then used for a series of seeded fault tests, before being rebuilt with all good parts and retested in August of 1995. Thus we have data from two "builds" of a main transmission assembly. Data from the 1994 runs is available only at one load condition (TQMR = 38K) and the 1995 runs have no data from sensor 3. By combining the test data from both builds/runs we have a comprehensive database for all sensors at all loads.

Baseline MM0396: This was a completely different build of Main Module 03, and two Input Modules, tested in February of 1996. There were no known discrepant parts in any of these three main transmission assembly modules, but a shim survey was being conducted, and no shim survey was completed.

Baseline MM0397: This was a completely different build of Main Module 03 and two Input Modules tested in May of 1997. There were no known discrepant parts in any of these three main transmission assembly modules, and no shim survey was conducted.

Table I: H-60 Drive Train Stress wave Sensor Locations

Stress Wave Sensor Number	Sensor Location
1	Port Input Module Input Housing
2	Port Input Module Output Housing
3	Starboard Input Module Input Housing
4	Starboard Input Module Output Housing
5	Main Module Planetary Ring Gear
6	Main Module Upper Cover
7	Tail Rotor Output/Rotor Brake Support Bracket
8	Forward Tail Rotor Shaft Bearing
9	Mid Tail rotor Shaft Support Bearing
10	Forward Disconnect Coupling Support Bearing
11	Intermediate Gearbox Disconnect Coupling Support Bearing
12	Intermediate Gearbox Input
13	Intermediate Gearbox Output
14	Tail Rotor Gearbox Input
15	Tail Rotor Gearbox Output

Case 1: Spalled rolling element (spherical roller) in a planetary gear. This was a fleet removal for debris generation.

Case 2: Main transmission starboard Timken (tapered roller) bearing. This was a fleet removal for debris generation.

Case 3: a) Main Module port input pinion gear spall (fleet reject).
b) 1/3 of a tooth removed from an Input Module input pinion. The pinion was machined to remove 1/3 of the working tooth at the toe side.

Case 4: Integral race spall in the Main Module starboard input pinion.

Case 6: Main Module port input pinion gear spall (fleet reject).

Case 7: Electron Discharge Machined (EDM'd) roller bearing in the Starboard Input Module, and EDM'd ball bearing in the Port Input Module.

Case 8: Electron Discharge Machined (EDM'd) roller bearing in the Starboard Input Module; EDM'd ball bearing in the Port Input Module; and Main Module Planet Gear Tooth fault.

Case 9: Same as CASE 7 (Electron Discharge Machined (EDM'd) roller bearing in the Starboard Input Module, and EDM'd ball bearing in the Port Input Module) with the addition of high vibration of High-Speed shaft.

MM02 baseline data and seeded fault cases 1, 2, 3, 4, and 6 were used to train and evaluate FDN's. MM03 and case 7, 8, and 9 data have not yet been added to the training database or used for evaluation of the FDN's developed thus far.

Data Reduction & Feature Extraction

Data Reduction: Approximately 160 hours of Stress Wave Pulse Train (SWPT) data were recorded during the 32 months of testing. This data is contained on 79 tapes that were correlated and cataloged with the Microsoft Access database, from the SWAN 3000 data acquisition system, and the Test Cell Data Logs provided by NAWC Trenton.

Data reduction began with the laborious task of locating specific data records on each of the tapes. The SWAN 3000 is a 2-channel data acquisition system. It was set up to lock channel 2 onto one sensor for continuous data recording during a test, while channel 1 would sequentially scan the remaining 14 sensors, plus a signal tone. The analyst first used the Access data base and the test cell log sheets to locate a particular operating (load) condition on the tape for a given test date. Then the tape was monitored to listen for the signal tone that identifies the end of one scanning sequence and the beginning of another. Data records were 15 seconds in duration, so by using an oscilloscope and a stopwatch it was possible to identify which of the sensors was the source of the recorded SWPT at any point on the tape. Each sensor's elapsed time location on tape was then entered into the data reduction log, so that it could be more easily retrieved for subsequent digitization, feature extraction, network synthesis, and system test.

The next step was to digitize the data from each sensor, at each load, for each test configuration. This was accomplished using the Transient Capture (TC) feature of the SWAN 3000. The analog SWPT data has a frequency content of 0 to 5000 Hz, before attenuation due to roll off characteristics of the demodulator in the system's analog signal conditioner. The SWPT data is therefore digitized at a 20 KHz sample rate (with 12 bit resolution) to satisfy Nyquist anti-aliasing criteria. Typically the "middle"10 -12 seconds of each record were used to create 5 Time History (TH) files (each of 2-second duration). This avoided including switching transients in the data, and provided files of the same length planned for use in the DPU. To date, approximately 2,200 of these TH files have been generated and stored in a computer directory as binary files.

Feature Extraction: Specialized Feature Extraction (FE) software has been developed for the purpose of accurately characterizing the SWPT and compressing the TH files. This custom SWAN Feature Extraction software is unique to the interpretation of the Stress Wave Pulse Train (SWPT) for the quantitative analysis of friction and shock events in operating machinery. The FE software is modular, and is available in two versions: the Analyst Mode, and the DPU Mode. The Analyst Mode includes a " WINDOWS shell" written in Visual Basic and is used in the PC environment to develop input tables for the

synthesis and test of DPN's. The DPU Mode is the operational form of the code, as required by the DPU and LTC components of the DSWAN system. Feature Extraction starts with the TH file of the SWPT. Mathematical transforms are then applied to the time series data for characterization of 37 time domain waveform features such as pulse amplitude, duration and energy content.

Fault Detection Networks (FDN's): FDN's are resident in each of the DPU's. Sufficient non-volatile memory has been allocated to store up to 32 FDN's in each DPU. These 32 FDN's will perform the function of "anomaly detection" for the 8 sensors connected to the DPU. When an anomalous condition is detected, the features will be stored for postflight download to the LTC ground station. The LTC software will then combine this data with trended data, and data from any other related sensors, for Enhanced Fault Detection, Fault Location, Fault Isolation, and estimating Percent Degradation.

The inputs to the FDN's are the time domain features extracted from each 2-second Time History file at each sensor location. The Analyst Mode of the TDFE software was used to extract the time domain features that were then used to train and evaluate the FDN's for sensor locations 1 through 5 on the H-60 main transmission assembly. MM02 baseline data and seeded fault cases 1, 2, 3, 4, and 6 were used to train and evaluate FDN's.

Before FDN synthesis can begin, input data tables of examples must be carefully constructed to train and evaluate various possible network configurations. Each row in one of these input tables is an example of Stress Wave Pulse Train time domain features for a given test configuration (baseline or seeded fault) and operating condition (main rotor torque (TQMR)). Each column, except the last, in an input table corresponds to one of the 37 time domain features. The value in the last column identifies the features in that row as either a baseline (0) or seeded fault (1) example.

A table must be prepared for each sensor location, and a separate set of five tables must be prepared for each of the five-seeded fault conditions. Each of these tables contains approximately 100 to 200 examples of both seeded fault and baseline conditions. About 1/3 to 1/2 of the data are from seeded fault conditions, and represents a full range of operating loads.

The basic strategy employed in the synthesis of the FDN's was as follows:

1. Train and evaluate first on a full normal load range of data. Train FDN's based upon two or more load ranges only if necessary to achieve satisfactory diagnostic accuracy.

2. Use a set of seeded faults that represent a range of fault types (gears and bearings) fault locations (input modules and planetary gear system) and damage levels.

3. First synthesize FDN's that are optimized for the detection of a specific fault type and location (fault specific). Then, given satisfactory accuracy for fault specific models, synthesize networks that are more generic, and capable of accurately diagnosing multiple types of faults.

4. Train all test models using 75% of the data, and reserve 25% of the data for FDN evaluation.

5. Employ parametric constraints in the modeling/synthesis process, to limit the complexity of the resulting FDN's. This is necessary both to limit the amount of executable code required to implement a model, and to avoid "over-fitting" the network to the available database.

Optimizing the Complexity Penalty Multiplier (CPM): The software used to synthesize and evaluate the network of polynomial equations (AbTech's ModelQuest Expert) has a user setable parameter called the Complexity Penalty Multiplier. The CPM is used to minimize a modeling criterion that attempts to select as accurate a network model as possible, without over fitting the data. Over fitting occurs when the network model becomes so specific to the training data that it does a poor job of evaluating new data. ModelQuest minimizes over fit by performing a trade-off between model complexity and accuracy, based on the assumption that simpler models are more general and superior for as yet unseen data (i.e. data not used for training).

In order to optimize the CPM for a given network, a model is set up with a given input table and set of modeling parameters such as the maximum number of hidden layers and the maximum number of inputs. This model is then exercised through approximately 10 iterations of varying the CPM and assessing the impact on the average absolute error of the network output. For the H-60 main transmission assembly, this iterative process was repeated for each of the five sensor locations for each of the five seeded fault cases. Then the FDN was resynthesized at the best CPM for each of the five sensor locations and each of the five seeded faults. (Thus the CPM optimization process required 275 modeling iterations.)

This entire CPM optimization process was repeated twice: first using all the data to train and 25% of the data (which had been used in training) to evaluate; then using 75% of the data to train and 25% to evaluate. The purpose of this exercise was to assure that the CPM was optimized based upon the full range of data, and to check if there was a significant difference in the optimized CPM when trained on a reduced data set. (If the optimum CPM from the reduced data set was significantly different, it would indicate the need to change the Random Number Seed in the model setup so that the full range of data would be used when training on only 75% of the data base.) In all cases, the FDN's saved for evaluation purposes, were those that were trained on 75% and evaluated on 25% that was not used in training.

Optimizing the Evaluation Threshold: The next step was to optimize the evaluation threshold for the "best CPM" model at each sensor location for each of the fault cases.

(This threshold is the value of the network output, between 0 and 1, above which a fault message is generated.) This optimization process consists of making a tradeoff between False Alarms and False Dismissals (undetected faults).

In the case of an aircraft like the H-60, the consequences of a false alarm are worse than that of a false dismissal. This is due to two principal reasons:

1. The probable consequences of a false inflight alarm range from a mission abort to an accident resulting from the hazards associated with a precautionary landing. A false post flight alarm will result in an unnecessary maintenance action, and possibly a premature, or incorrect, component removal.

2. The probable consequences of an undetected fault are not as serious, mainly because there will be more opportunities to detect the problem as additional measurements are made. With each additional scan of the sensor and application of the FDN, the cumulative probability of detection will increase. Since the sensor will be scanned at least once every 18-20 seconds, there will be about 200 opportunities for the FDN to find the problem during each hour of operation. As the problem develops during subsequent hours of operation, the symptoms of the problem will also become increasingly clear, and the probability of detection will be increased even further.

For these reasons, and prior quantitative analysis of their implications for helicopter fleets, the alarm threshold must almost always be optimized to cut the false alarm rate to a minimum. 25 iterations of threshold optimization were performed: one for each of 5 sensor locations, for each of the 5 seeded fault conditions. Tables II through VI show the false alarm and false dismissal rates for the best of these **fault specific** FDN's at each of five sensor locations, for seeded fault cases 1, 2, 3, 4, and 6. These results show that for each seeded fault, at least 3 out of five sensor locations had FDN's that were 100% accurate, when tested on data that had not been used in training. This was sufficiently encouraging to proceed to the next step of the overall FDN development strategy: synthesis and test of FDN's capable of detecting multiple types of seeded faults.

Table II: FDN Diagnostic Accuracy, Case 1
(spalled planet bearing roller)

Sensor Location	Evaluation Threshold	False Alarm %	False Dismissal %	Comments
1	0.50	0.00	0.00	
2	0.50	0.00	0.00	
3	0.65	5.70	5.70	
4	0.65	2.80	2.80	
5	0.50	0.00	0.00	closest sensor & most accurate FDN

Table III: FDN Diagnostic Accuracy, Case 2
(MM input pinion Timken Bearing)

Sensor Location	Evaluation Threshold	False Alarm %	False Dismissal %	Comments
1	0.50	0.00	0.00	
2	0.50	0.00	0.00	closest sensor
3	0.40	0.00	0.00	
4	0.50	0.00	0.00	
5	0.50	0.00	0.00	most accurate FDN

Table IV: FDN Diagnostic Accuracy, Case 3
(MM input pinion gear spall, IM input pinion ground-off tooth)

Sensor Location	Evaluation Threshold	False Alarm %	False Dismissal %	Comments
1	0.55	0.00	0.00	
2	0.66	3.10	3.10	closest to gear spall
3	0.50	0.00	0.00	
4	0.65	0.00	0.00	
5	0.50	0.00	0.00	most accurate FDN

Table V: FDN Diagnostic Accuracy, Case 4
(MM input pinion roller bearing spall)

Sensor Location	Evaluation Threshold	False Alarm %	False Dismissal %	Comments
1	0.50	0.00	0.00	most accurate FDN
2	0.45	0.00	0.00	
3	0.50	0.00	0.00	
4	0.50	0.00	0.00	closest sensor
5	0.50	0.00	0.00	

Table VI: FDN Diagnostic Accuracy, Case 6
(MM input pinion gear spall)

Sensor Location	Evaluation Threshold	False Alarm %	False Dismissal %	Comments
1	0.65	0.00	5.70	
2	0.50	0.00	0.00	closest sensor & most a accurate FDN
3	0.50	0.00	0.00	
4	0.50	0.00	0.00	
5	0.45	0.00	2.90	

Three approaches were considered for development of multi-case FDN's:

1. Develop two FDN's; one for gear faults, and the other for bearing problems, at each of the five sensor locations.

2. Develop one FDN for each sensor location, that is capable of diagnosing both gear and bearing faults.

3. Develop one generic FDN that can detect all problems, at all sensor locations.

The first approach was the least desirable of the three, and the third was the most desirable. The third approach seemed rather ambitious, and was likely to result in higher false alarm and false dismissal rates than the second approach. Based upon the results of the second approach, subsequent development could be pursued using the first or third. Thus we elected to synthesize new multi-case FDN's based on the second approach.

This first required creating a new set of five input data tables (one for each sensor location). These tables contained the same baseline data as used in the fault specific model synthesis, but included discrepant data from all five of the previously described seeded faults. After creation of these input tables, model synthesis followed the same strategy and procedures that were used for synthesis and test of the single fault FDN's.

The results of this process and the threshold optimization for each sensor's multi-case FDN are shown in Table VII. This shows that 3 out of 5 multi-case FDN's demonstrated false alarm rates of 1% or less when tested on data not used in training. If "3 out of 5" voting logic is applied to the thresholded output these five multi-case FDN's, the results should be sufficiently accurate.

Table VII: FDN Diagnostic Accuracy
(Case 1, 2, 3, 4, and 6)

Sensor Location	Evaluation Threshold	False Alarm %	False Dismissal %	Comments
1	0.95	1.00	14.00	
2	0.80	0.00	14.00	
3	0.50	2.30	0.00	
4	0.85	3.40	3.40	
5	0.50	0.00	3.00	most accurate multi-case FDN

Summary: The integration of SWAN with polynomial network modeling shows good potential for producing accurate diagnostics with low false alarm rates. The synthesized Fault Detection Networks (FDN's) are quite compact, and capable of being implemented by, small Distributed Processing Units (DPU's). These DPU's can function autonomously, or can be modular additions to existing aircraft systems such as Flight Data Recorders and Health Usage Monitoring Systems.

Ongoing work will include expansion of the training database to include additional seeded fault and baseline data. Additional testing will include evaluation of the best FDN's using baseline and fault data that not only was not in the training database, but was acquired from assembled gearboxes that were not in the training database. Frequency Domain Feature Extraction will be applied to the data, and used to train Fault Location and Fault Isolation Networks (FLN's & FIN's) that can pinpoint the root cause of an alarm from an FDN. Other networks for Percent Degradation, Regime Recognition and Sensor Validation are also being developed.

A Study of the Applicability of Atomic Emission Spectroscopy (AES), Fourier Transform Infrared (FT-IR) Spectroscopy, Direct Reading and Analytical Ferrography on High Performance Aircraft Engine Lubricating Oils

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Abstract: The Joint Oil Analysis Program Technical Support Center (JOAP-TSC) was tasked by the U.S. Air Force to determine the appropriateness of various oil analysis techniques to provide early warning of abnormal operating conditions. The study analyzed ~1300 samples from F-16, F110-GE100 gas turbine engines by spectroscopy (AES and FT-IR) and direct reading and analytical ferrography. A statistical analysis of the data collected is presented.

Key Words: Analytical ferrography; atomic emission spectroscopy; condition monitoring; direct reading ferrography; Fourier transform infrared spectroscopy; FT-IR; JOAP; JOAP-TSC; oil analysis.

Introduction: The U.S. Air Force Oil Analysis Program (AFOAP) uses atomic emission spectroscopy for determination of equipment wear. This study was initiated to determine whether or not there were any aircraft engine failure modes that *only generate wear metals too large to be measurable by AES.* In addition, oil failure modes such as contamination and degradation were monitored to determine any potential correlation with mechanical failure modes. With the exception of the Complete Oil Breakdown Rate Analyzer (COBRA) [1 & 2] test for PW-F100 engines, the AFOAP does not monitor oil condition. The General Electric F110-GE100 engine was chosen by the Air Force for this study.

Test Equipment and Methods: The JOAP-TSC analyzed F110 engine samples (from Pope AFB and Cannon AFB) by atomic emission spectrometry (AES), analytical ferrography, direct reading ferrography (DRIII) and Fourier transform infrared (FT-IR) spectroscopy. A database was created using pertinent squadron information obtained from the DDF 2026, sample submission form. To speed sample and statistical analyses, the AES, DRIII and FT-IR were linked via a LAN system for automatic data entry into the database. Manual entry was required only for the analytical ferrography data.

The following approach was taken for sample analysis.

a. The Air Force analyzed all samples by AES and forwarded them to the JOAP-TSC.

b. The JOAP-TSC analyzed all samples by AES (Baird MOA) and FT-IR (Bio-Rad "Oil Analyzer"). The JOAP-TSC AES results were similar to the Air Force's AES results.

c. Approximately every fifth sample was analyzed by DRIII and analytical ferrography (Predict/DLI). This approach was taken due to the amount of time required for analytical ferrography and the small sample volume—20 ml bottles—generally with only 5 to 10 mls remaining. If the fifth sample did not have sufficient oil, the fourth or sixth sample was chosen, if volume permitted. In the case of abnormal results from any test (AES, FT-IR or ferrography) and volume permitting, the intermediate samples were analyzed by analytical ferrography. The tests were generally performed in the following order: DRIII, ferrrography, FT-IR and AES. Note: AES was performed at field laboratories on all samples.

d. AES analysis guidelines were taken from T.O. 33-1-37-3 [3].

e. Fluid condition/contamination levels for FT-IR were based on preliminary studies of over 1000 polyol ester lubricant (Mil-L-7808) samples [4].

f. No statistical guidelines or limits were available for the ferrographic analysis of oil in F110-GE100 engines.

Results Analysis: The study evaluated over 1300 samples taken from 48 engines (28 aircraft). Engines removed for phase often returned to the study in another aircraft. The results were compared to available limits and trended over time. The trend calculations required multiple samples (same engine) consequently, the number of samples for which trends were calculated is lower (686). Scheduled engine removals occurred throughout the study further limiting the number of samples from any single engine.

The sample data was used to calculate limits based on average and standard deviation data. The AES calculated limits were compared to the engine T.O. limits to examine limits behavior. Differences between predicted and T.O. limits are discussed under exceptions. Example data is shown as trend plots along with explanations. Please note, there were no high wear or severe fluid condition or contamination indicators observed during the project. Field laboratories reported no engine failures had occurred.

Ferrography/Particulate Analysis: The severity of wear for the F110 engine was established by empirical means—subjective operator experience [5]. The severity of wear for each of the named wear modes is characterized by the index 0 (none) to 4 (severe). The index is specific to this engine and this study.

The most commonly seen particles were created by normal rubbing wear and bearing wear. Neither of these wear modes were seen in critical amounts. Some black oxides, red oxides, sand and fibers were also seen in trace amounts. Molybdenum disulfide, used as an anti-seize compound on fasteners, was also common. The majority of sample slides were clean—no particulate debris. Since there were no wear related failure modes, the DRIII results were nominal.

Particle Exceptions: There were a few instances of metal particles larger than 100 microns when AES and FT-IR were normal. The large particles were not present in subsequent samples and are not believed to have been related to any failure mode. Table I shows an example. Table II contains the statistics and limits for all ferrography data.

Sample ID	Date	CHUNKS NF	CHUNKS NF	LAMINAR	LAMINAR S	LAMINAR
96S00169	Apr27/96	0.00	0.00	2.00	20.00	0.0
96S00170	May2/96					
96S00171	May2/96					
96S00172	May2/96	0.00	0.00	0.00	0.00	1.0
96S00173	May6/96					
96S00174	May7/96	1.00	140.00	1.00	10.00	1.0
96S00221	May7/96					
96S00294	May7/96	0.00	0.00	1.00	16.00	0.0
96S00295	May8/96	0.00	0.00	1.00	0.00	0.0
96S00296	May13/96					
96S00343	May14/96	0.00	0.00	0.00	0.00	0.0
96S00344	May14/96					
96S00345	May15/96					
96S00368	May21/96	0.00	0.00	1.00	18.00	0.0
96S00369	May21/96					
96S00370	May29/96	1.00	40.00	0.00	0.00	2.0

Table 1: Example of Wear Particle Results

Atomic Emission: All AES results for most samples were within limits. An occasional sample indicated an elevated level or trend, primarily for molybdenum and zinc. Generally, subsequent samples showed normal readings (Table III). Spurious data such as this raises suspicions of contaminated samples or poor tests. Molybdenum disulfide is used as an antiseize compound on fasteners and can potentially enter the oil. Zinc is a common component of additives in ground vehicle lubricants and is also found in copper alloys and galvanized steel. The source of the zinc in these cases is unknown.

Sample Date	PPM Zn
15 Jan	1
16 Jan	14
16 Jan	0

Table III. Example of Zinc Data (all samples analyzed on the same day)

Table II: DRII and Analytical Ferrography Statistics and Limits

Parameter Name	Type	Number of Samples	Average	Std Dev	Min	Max*	Calculated Limits 2 Std Dev	Calculated Limits 4 Std Dev	Existing Limits Marginal	Existing Limits High
Blk Oxides	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
Red Oxides	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
Rubbing Wear	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
Fibers	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
Fiction Polymers	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
Mo Disulfide	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
Corrosive Wear	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
Sand/Dirt	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
Chunks Ferr	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
	size	274	3.34	n/a	0	200	n/a	n/a	none	none
Chunks Non-Fe	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
	size	274	8.86	n/a	0	200	n/a	n/a	none	none
Cutting Wear Fe	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
	size	274	0.78	n/a	0	40	n/a	n/a	none	none
Cutting Wear Non-Fe	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
	size	274	0.93	n/a	0	44	n/a	n/a	none	none
Laminar Fe	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
	size	274	2.69	n/a	0	50	n/a	n/a	none	none
Laminar Non-Fe	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
	size	274	4.52	n/a	0	180	n/a	n/a	none	none
Sliding Fe	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
	size	274	3.49	n/a	0	130	n/a	n/a	none	none
Sliding Non-Fe	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
	size	274	0.38	n/a	0	40	n/a	n/a	none	none
Spheres	level	274	n/a	n/a	0	n/a	n/a	n/a	none	none
	size	274	0.25	n/a	0	6	n/a	n/a	none	none
DRIII Large Part	level	286	2.19	1.37	0.00	11.60	4.93	7.67	none	none
DRIII Small Part	level	286	1.36	0.83	0.00	5.80	3.02	4.68	none	none
DRIII PLP	percent	286	22.59	22.67	0.00	100.00	n/a	n/a	none	none
DRIII WPC	level	286	3.52	1.92	0.30	14.10	7.36	11.20	none	none

Size values are in microns

*Note: Maximum value could not be determined due to lack of failure data

The predicted limits from the study are well below the T.O. limits. This difference is due to the very clean sample set, i.e., there are no failure modes represented. Table IV contains the statistics and limits for all atomic emission data.

Lubricant Condition (FT-IR): The severity of oil condition indicators were based on prior work with Air Force, Army and Navy aircraft FT-IR analysis. Most samples were normal—no indication of serious lubricant contamination or degradation. However, a change (loss) in antiwear additive level was noticed between makeup oil additions. If oil additions were made frequently (small quantities—one half to one pint), the change in antiwear levels was nominal. When large quantities of make-up oil were added (2 to 3 pints)—indicative of longer engine runtimes, the corresponding drop in antiwear additive was significant (Figure 1). The impact of the decrease in antiwear additives on engine reliability is beyond the scope of this study.

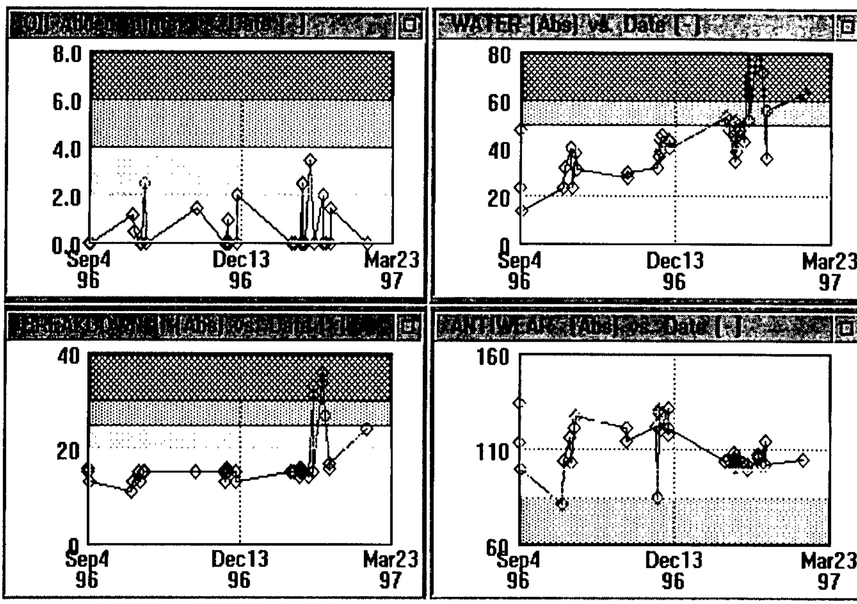

Figure 1. Example of Data Trends (Note: Out of limit areas are shaded.)

The study also indicated water contamination in excess of current alarm levels (45 = 1000 PPM). In addition, a few significant water contamination problems (water greater than 2000 PPM) were noted. High levels of water were always associated with some lubricant degradation (Figure 1). Water contamination is a known cause for polyol ester lubricant breakdown. Engine operating conditions (high temperatures) in conjunction with oil

Table IV: AES Statistics and Limits

Parameter		Number of					Calculated Limits		Existing Limits	
Name	Type	Samples	Average	Std Dev	Min	Max	2SD+Ave	4SD+Ave	Marginal	High
Ag	level	1321	0.01	0.12	0.0	3.0	0.25	0.49		
	trend	686	0.00	0.12	n/a	1.2	0.23	0.46	n/a	2
Al	level	1321	0.06	0.28	0.0	4.5	0.64	1.22	4	7
	trend	686	0.03	0.29	n/a	3.2	0.60	1.18	n/a	2
B	level	1321	0.03	0.11	0.0	2.0	0.25	0.47	none	none
	trend	686	-0.01	0.12	n/a	0.8	0.23	0.47	none	none
Ba	level	1321	0.01	0.12	0.0	2.0	0.25	0.49	none	none
	trend	686	-0.01	0.12	n/a	0.8	0.23	0.47	none	none
Cd	level	1321	0.16	0.41	0.0	4.0	0.98	1.80	none	none
	trend	686	0.00	0.36	n/a	2.1	0.72	1.44	none	none
Cr	level	1321	0.02	0.12	0.0	1.2	0.26	0.51	7	10
	trend	686	0.01	0.11	n/a	1.1	0.23	0.46	n/a	2
Cu	level	1321	0.76	0.64	0.0	5.0	2.05	3.34	13	20
	trend	686	-0.01	0.32	n/a	1.7	0.64	1.28	n/a	4
Fe	level	1321	0.09	0.34	0.0	8.3	0.76	1.43	9	14
	trend	686	0.00	0.19	n/a	1.0	0.39	0.78	n/a	3
Mg	level	1321	0.43	0.45	0.0	4.0	1.33	2.22	7	10
	trend	686	-0.01	0.39	n/a	2.9	0.77	1.54	n/a	2
Mn	level	1321	0.21	1.02	0.0	7.4	2.25	4.29	none	none
	trend	686	0.17	0.92	n/a	7.0	2.01	3.85	none	none
Mo	level	1321	1.09	1.02	0.0	11.0	3.13	5.16	3	5
	trend	686	0.12	0.86	n/a	10.5	1.84	3.56	n/a	2
Na	level	1321	5.71	2.60	0.0	18.7	10.91	16.11	none	none
	trend	686	0.12	2.24	n/a	12.7	4.60	9.08	none	none
Ni	level	1321	0.03	0.15	0.0	1.4	0.34	0.64	6	9
	trend	686	-0.02	0.18	n/a	1.0	0.35	0.71	n/a	2
Pb	level	1321	0.21	1.06	0.0	9.4	2.33	4.45	none	none
	trend	686	0.04	0.97	n/a	6.5	1.98	3.92	none	none
Si	level	1321	0.78	1.64	0.0	22.8	4.07	7.36	13	20
	trend	686	0.02	1.63	n/a	18.3	3.28	6.54	n/a	5
Sn	level	1321	5.53	1.52	0.0	15.3	8.57	11.61	none	none
	trend	686	-0.02	1.63	n/a	9.5	3.24	6.50	none	none
Ti	level	1321	0.14	0.29	0.0	3.3	0.72	1.31	6	9
	trend	686	-0.03	0.29	n/a	1.9	0.55	1.12	n/a	2
V	level	1321	0.77	1.52	0.0	28.2	3.81	6.85	none	none
	trend	686	0.07	0.76	n/a	10.3	1.59	3.11	none	none
Zn	level	1321	0.79	2.45	0.0	35.5	5.70	10.61	3	5
	trend	685	-0.07	2.66	n/a	16.2	5.26	10.58	n/a	2

Table V: FT-IR Statistics and Limits

Parameter		Number of					Calculated Limits		Existing Limits	
Name	Type	Samples	Average	Std Dev	Min	Max	2 Std Dev	4 Std Dev	Marginal	Abnormal
Water	level	1348	36.42	15.06	8.0	95.0	66.53	96.64	n/a	45
Breakdown I	level	1348	24.04	3.71	12.0	38.0	31.45	38.87	n/a	65
Breakdown II	level	1348	15.72	3.66	11.0	37.0	23.05	30.37	n/a	25
Antiwear*	level	1348	110.99	10.82	80.0	147.0	89.35	67.71	n/a	80
Fuel Dilution	level	1348	189.32	2.10	184.0	195.0	193.52	197.73	n/a	201
Other Fluid	level	1348	12.97	8.08	0.0	43.0	29.14	45.30	n/a	30

FT-IR values and limits are in Absorbance units

Note: water 45 Abs = 1000 PPM; breakdown I and II are for TAN of ~1.5 mg of KOH/ml

*Note: antiwear limits are calculated below mean

additions corrected both the water and degradation problems. Consequently for aircraft with frequent oil additions, water contamination levels should only be a concern if present during extended periods of non-operation. Table V contains the statistics and limits for all FT-IR data.

Conclusions: There was no data to corroborate the hypothesis of the study—that large wear particles are generated in the absence of smaller wear particles measurable by AES. In retrospect, there were insufficient samples to ensure that no relationship exists. In addition, no oil related engine failure modes were observed during the study and no engines were replaced because of mechanical defect or failure.

AES appears to generate reliable results for aircraft engine wear analysis. DRIII results were unreliable due to the low level of normal wear debris—very clean oil. *In the absence of engine failures,* the behavior of the DRIII readings and ferrography on samples indicating severe wear could not be determined.

Acknowledgements: The authors would like to thank Pope Air Force Base and Cannon Air Force Base for supplying the oil samples.

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The Application of Time Resolved Dielectric Instruments to Air Force Ground Fleet Maintenance

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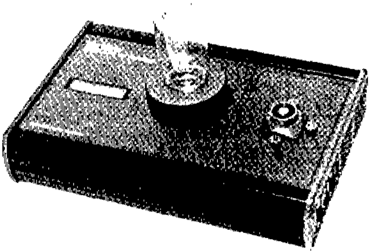
Abstract: In 1993 the Military Equipment Evaluation Program (MEEP) located at Eglin Air Force Base, FL, evaluated a time resolved dielectric instrument for use in air force ground fleet maintenance applications. They identified this instrument as a useful device for what they termed "bumper testing" intended to measure oil quality before changing oil rather than simply changing oil based on calendar months or equipment usage (miles or hours).

Since that time the instrument has been accepted and is in use at many U.S. Air Force installations world wide. Typically an air base will have apploximately 40 ground vehicles for every one flight vehicle. For example, Eglin has approximately 1200 ground vehicles supporting 30 fighting aircraft. The aircraft get oil analysis done very frequently. Until the time resolved dielectric instrument was made available, no oil analysis was performed on the ground fleet.

This paper describes the application, use and results achieved by using a multifunctional oil analyzer in the maintenance shops to determine oil conditions before taking maintenance actions.

Key Words: By-pass filters, condition-based oil change, time-resolved dielectric measurement, ferrous, Management and Equipment Evaluation Program (MEEP), Pacific Air Force Command



Introduction: In 1993, new federal and local legislation effectively increased the cost of changing oil on a timely or mileage-based schedule by tightening regulations related to the disposal of used oil. This prompted the Air Force to research cost-effective ways to analyze vehicle oils. After careful research, the United States Air Force Military Equipment Evaluation Program approved CSI's OilView Analyzer for use in vehicle maintenance.

The research confirmed several things. Often the lubricants being discarded still retained good friction reducing, cooling, cleaning, and corrosion prevention properties. Changing oil based on the condition of the oil is less expensive than changing it based on its age or on the number of miles it has been in the vehicle. And thirdly, the technology is available to perform this analysis easily in the vehicle maintenance facility itself, eliminating the necessity of shipping lubricant samples to a laboratory.

Obviously, costs associated with purchasing new lubricants can be cut when lubricants are purchased less frequently. And costs associated with waste oil disposal are decreased when less waste is produced.

Implementation: The Pacific Air Force Command developed and implemented an oil analysis program based on the capabilities provided to them by the time resolved dielectric testing features of the instrument. "Of the three units tested, [the OilView Analyzer] gives the most comprehensive analysis, with results just short of that obtained from an oil analysis laboratory... Test results were confirmed via lab results of the same oil samples provided by the Department of Defense oil lab at Pensacola NAS."[1] Special oil filters were also recommended, but were not a mandatory part of the program. "The analysis equipment and by-pass filters qualify for Pollution Prevention Program (PPP) funding for their initial purchase."[2]

Information comparing used oil conditions and contamination to new oil is used to determine whether the oil should be changed or filtered. This data is stored, plotted, and analyzed in order to maintain a historical record, plotted and analyzed.[3] When the condition or contamination of the oil deteriorates to a pre-determined point, the oil is changed. Otherwise, it is left alone until the oil is no longer functional.

Though the analyzer also provides information about the wear condition of an engine, it is not used for engine analysis by PacAF. It is not cost effective to do work on most ground vehicle engines unless it has obvious operational problems. Even if the ferrous content of the oil is high, the engine will simply be changed out when a problem develops. On the larger equipment, like snow plows, engine analysis might be useful and cost effective, but research must be done to verify this before a program can be implemented.[4]

Because improper sampling techniques will skew the analysis results, all personnel upon which the program depends must be dedicated to its success. The Vehicle Maintenance Manager designates one person to be trained as the oil analyst, but the base members that fall into the role of customer must also be educated about the new program. To accomplish this during the startup phase of the program, the VMM may establish a cross-functional Process Action Team made up of maintenance supervisors, workers, and outside organizations that represent the various groups of vehicle maintenance customers.[5]

"Operator servicing of the engine oil presents the greatest potential for crankcase contamination," so the oil is changed and the majority samples are taken only in the vehicle maintenance facility by the analyst.[6] This change from the old way of doing things must occur at the same time that the interval between oil services is changed. These changes require, "the cooperation of all vehicle users in addition to 100 percent support from the vehicle maintenance team if it is to be creditable and successful."[7]

Sampling and Testing: Once all parties have agreed to the changes that must take place for the program to begin, the sampling interval must be established. "Analysis works best when intervals are based on the following three criteria: fuel consumption, established scheduled maintenance interval, and/or every six months."[8] Programs that are phased in

rather than implemented all at once will probably use all three criteria at some time or another.

Once all vehicles have been phased into the oil analysis program, "fuel consumption is the most effective means in determining when to analyze engine oil. This criteria tracks engine use regardless of vehicle use. Data from our test program indicates oil analysis must be accomplished every 300 gallons of fuel used for diesel and gasoline engines."[9]

The Pacific Air Force Command uses a computer program to track the fuel consumption of each vehicle by its identification number and the amount of fuel pumped into the tank. "When, according to the Materiel Transaction Listing, the vehicle's fuel consumption exceeds 300 gallons since the last oil analysis, an oil sample must be obtained and analyzed to determine its condition." [10] The operator brings the vehicle into the CSC where an oil sample is taken. If moving the vehicle is inconvenient, the oil analyst will go into the field and collect the sample just after the operator shuts off the vehicle, so that a representative sample is retrieved.

The data from the test run on the sample is compared to the data of the clean reference oil. The state of deterioration or contamination of the oil is rated according to levels preset by the Pacific Air Force Command. Each type of oil tested is given its own alarm levels or limits beyond which the oil is considered "good," "fair," "marginal," "bad" or "extreme." A lube condition of "good" or "fair" requires no further action in servicing the engine oil... A "bad" or "extreme" lube condition requires replacement of engine oil, all OEM oil filters, and replacement of any by-pass filter elements."[11] A "marginal" alarm requires the replacement of one of the by-pass filter elements if by-pass filters have been installed.

When water is found in the oil, another sample is drawn and tested to eliminate human error. If the second oil analysis also indicates water in the oil, than maintenance will conduit additional troubleshooting by other techniques to verify coolant is not leaking into the oil.[12]

Results: Currently there are five Pacific Air Force Command bases using the condition-based oil change program rather than a timely or mileage-based program. These bases are: Hickam AFB, HI; Elmendorf AFB, AK; Eielson AFB, AK; Anderson AFB, Guam and Kadina AFB, Japan. Soon, Ukoda AFB, Japan, will be moving to condition based oil changes as well.[13] Specific information on four of the five programs follows.

Hickam AFB, HI: Hickam Air Force Base has the largest of the four programs. Fifty to sixty samples are drawn and tested daily from 5000 ground vehicles. This represents half of the fleet of ground vehicles. The range of vehicles in the program includes: construction equipment, sedans, and snow equipment. Before the oil analysis program, each vehicle used, on average, 4.2 gal of oil per year. The quantity dropped to 1.8 gal/year After starting the program the quantity used dropped to 1.8 gal/year.[14]

Hickam Air Force Base has owned the testing equipment since 1995 and was the first to implement the oil analysis program as a part of the testing phase. The rest of the bases use the manual that was produced by officials involved in this phase of implementation as a blue print for their own programs.[15]

Eielson AFB, AK: Eielson Air Force Base has been performing condition-based oil changes for 2.5 years. There are 860 vehicles in the oil analysis program, including: fork lifts, graders, bulldozers, snow plows, regular pick-up trucks, and police cars. Testing intervals, based on fuel consumption, dictate a sampling rate of around 80 vehicles per month.[16]

As a result of condition-based oil changes at Eielson Air Force Base, between 340 and 400 quarts of oil is saved each month. This oil savings represents an even greater dollar amount than it would at other bases because of the expensive synthetic oil necessitated by the harsh north Alaskan climate. *Note of interest:* It has been found that there are cases in which oil in an engine remains usable for up to two years. Previous to condition based oil changes, this oil would have been discarded four times in two years.[17]

Elmendorf AFB, AK: There are 1200 vehicles in the oil analysis program at Elmendorf Air Force Base. The range of vehicles tested includes pick-up trucks, heavy equipment, forklifts, dump trucks, refuelers, graders, and cars. 10W30 and 15W40 are the two types of oil used and tested. Due to a recent personnel change in the Elmendorf role of oil analyst, no further information is available on the program there; however, the program is run in accordance with the guidelines established during the initial test at Hickam.[18]

Kadina AFB, Japan: Oil analysis equipment has been in use at Kadina Air Force Base in Japan since June of 1995. Fifteen to eighteen samples are taken daily from the fleet of 2000 cars, light and medium trucks, and heavy construction equipment. The only oil used in the is 15W40. As a result of the condition based oil change program, there has been a reduction in the amount of oil purchased, as well as a reduction of the base's hazardous waste.[19]

Conclusion: Implementing and applying the time-resolved dielectric measurement by the Pacific Air Force Commands Vehicle Maintenance Manager has brought benefits other than simple oil savings. "In addition to reducing waste oil generation, collateral benefits include: reduced acquisition of petroleum based lubricants, reduced labor hours in the management of waste oil, a reduction in risk assessment incurred during storage, pumping, and shipping waste oil, and an extension of engine life through improved, in use, lubricant . . . ."[20]

The oil analysis equipment purchased is flexible enough to allow expansion of the analysis program to include other applications. In fact, the Pacific Air Force Command is now planning to use the equipment to test oils in hydraulic systems.[21]

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FAILURE OF COMPONENTS ALTHOUGH THE CAUSES ARE SIMPLE & WELL DOCUMENTED

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Abstract: For most of the materials commonly used in machinery, the static, fatigue and other design properties have been well-studied and documented. Yet, very common and simple oversights are made in choosing the right material and the correct design for an application, leading to premature failure of components in pieces of equipment. This paper will present two failures caused by inadequate design and improper material selection.

1) Failed pawls in hand operated winches for ladder hoist: A pawl finger is used in the winch which engages in-between the teeth of two gears to lock the winch in place when weight is on the ladder extension. Occasionally, the pawl sustains failure. Determination of the cause, as well as recommendations for improvements will be discussed.

2) Failed "Power Lock" Tapered Ring: This device was designed to fasten a sprocket to a shaft without the use of keyways. The power lock consisted to two tapered rings bolted together with six bolts, wedged against an outer and inner ring. One of the tapered rings fractured during a bench test. The root cause analysis and recommendations for prevention is provided.

Key Words: Fatigue; inclusion; pawl; power lock; resulfurized; spring strip.

Failed Pawls in Hand Operated Winches for Ladder Hoist

Background: The hand operated winch to hoist ladders mainly operates with two gears. The "pawl" is a component in the piece of the equipment which engages in-between the teeth of the two gears to lock the winch in place, when hand cranking forces are released. Occasionally, the pawl is not properly engaged and is caught on the crest of the gear tooth. Then the reverse rotational forces bend the pawl as it jams the gears. The pawl finger was designed with a spring steel strip made from 301 stainless steel. This spring strip would allow some bending of the pawl finger when improperly engaged. But many failures of the pawl finger assembly had been reported.

Investigation: A few fractured pawls were examined to determine the root cause of the failure. Figure 1 shows a new pawl finger as viewed from one side. The spring plate is "sandwiched" in the bracket and the two sides of the bracket are welded in four locations (small arrows). The longer arrow is pointing to the pawl weight and the thicker arrow is showing the fulcrum bushing.

Binocular Microscope Examination: The spring strips always failed in an area that is unsupported by the bracket. Figure 2 presents an overall view of a failed pawl. Some plastic deformation was observed near the fractured surfaces of the spring strips.

Two samples, numbered 1 and 2, were selected for in-detail investigation. The overall view of the fracture surface for sample #1 is shown in Figure 3. Multiple origins were observed from the pawl weight side of the spring strip (small arrows). The "thumbnail shaped" features around the origins and relatively smooth fracture surface are typically associated with fractures that grow with operational time. The origins show radial markings emanating from them. The "thumbnail shaped" appearances radiating outward from the origins are macroscopic progression marks on a fracture surface which indicate positions of the advancing crack front. The final overload area was on the opposite side of the strip and measured approximately .004" in thickness (12% of the total thickness of the plate). This area is shown by the longer arrows in Figure 3.

The second sample also revealed similar features on the fracture surface but the origins were located on the opposite side or on the "flex" side of the spring.

Scanning Electron Microscopy: The fracture surfaces from the samples were examined at higher magnifications for determination of the fracture mode. The origins were always from the same side and from the surface. No anomalies were observed at or near the origins. Fatigue striations were visible emanating from the origins. Figure 4 presents an area with striations. Each striation indicates the position of the crack front after each succeeding cycle of stress or loading and are indicative of fatigue fracture.

Optical Microscopy: Cross-sections were made through the origins of the two fractured samples. No microstructural anomalies were found in the samples. The microstructure consisted of heavily worked elongated austenite grains, typical of full hard 301 stainless steel (SS). Figure 5 shows an overall view of the mounted cross-section through one of the origins of sample #1. The longer arrow shows the origin. The fracture was predominantly transgranular and showed many secondary cracks (small arrows). The small thicker arrows on the left-hand side of Figure 5 show initiations of other fatigue cracks, parallel to the fracture surface (FS).

A few cross-sections were made at the welds close to the failed spring strips; no microstructural change was observed on the strips near the welds.

Hardness and chemical analysis results meet the material specification requirements.

Conclusions and Discussion: The failed pawls fractured by fatigue in the center area of the spring strip. When the pawl fails to engage itself properly in-between the gear teeth, it experiences a significant amount of bending, causing permanent plastic deformation and locally damaging the spring metal. The material used for the spring strip, 301 stainless steel (full hard), is very notch sensitive. The magnitude of the applied cyclic vibrational forces on the spring strip when the pawl snaps off the top of the gear tooth

were large enough in the permanently bent areas to exceed the capability of the component and to initiate fatigue cracks. Continued use caused the fatigue cracks to grow to failure.

No material anomalies were observed. The welding performed on the pawl finger brackets was away from the fractures and the welding process did not contribute to the failures of the pawls.

Recommendations: We suggest a change in the shape of the tip of the pawl, which would be a retrofit to the existing pawls. Instead of the present rounded tip, the end should be ground so that the inner diameter side of the bracket makes an angle of about 40-45 degrees with the pawl weight side (outer diameter side) of the bracket (Figure 6). This reduces the contact area between the pawl tip and the gear tooth and the angled surface helps the pawl slide down to nest between the gear teeth. There is less chance of the pawl tip to get caught on the gear crest. The crests of the big gear teeth should be smoothed so that there are no burrs.

<u>Alternative Materials for the Spring Strip</u>: Other spring materials which can be used instead of the 301 SS are 410 SS and 420 SS, PH13-8Mo SS and Custom 450 SS. The 410 and 420 SS are martensitic in the hardened condition. They can be heat treated/tempered to the required mechanical strength. PH 13-8Mo and Custom 450 are precipitation hardenable stainless steels. These steels have better fatigue properties than the currently used cold-worked 301 SS. They also have good corrosion resistance and high strength and should serve the purpose when used in the pawl.

Failed "Power Lock" Tapered Ring

Background: A failed "Power Lock" device, used to fasten a sprocket to a shaft, consisted of two tapered rings (Ring A and Ring B) bolted together with six bolts holding an outer and inner ring. Ring A reportedly fractured during a bench test. The rings are made from SAE 1144 steel (a resulfurized grade).

Investigation
<u>Binocular Microscopy</u>: The Power Lock was disassembled, Figure 7, and examined with a binocular microscope. Cracks were observed on both sides of a drill hole in ring A, at the thinnest section. The arrow in Figure 7 is pointing to the crack. There were no cracks at any of the remaining drill holes.

The crack was broken open and the fracture surface was examined, Figure 8. The portion of the fracture surface on the "inside radius" (bottom surface in Figure 8) had a "woody" type fracture appearance, indicative of the longitudinal direction of the original bar stock. The portion of the fracture surface on the "outer radius" (top surface in Figure 8) in the thin section appeared "woody" and dull, measuring approximately ¼", and the thicker section (the remaining ⅛") was shiny and rough. The "woody" appearance is typical of transverse fractures through cold drawn steel products. The drawing operation elongates

the grains improving the yield strength of the bar in the longitudinal direction, while reducing the transverse properties.

Scanning Electron Microscopy: High magnification examination of the outer radius fracture revealed that the thin end of the fracture had two "smooth" linear regions extending to the tip. Figure 9, at higher magnification, shows the tip of the fracture surface containing one of the smooth features. Energy dispersive x-ray spectroscopy was performed on the smooth linear portion and rough portion of the fracture surface. Analysis of the smooth surface revealed a major concentration of iron, minor concentrations of sulfur and manganese, and a trace of oxygen, indicative of a manganese sulfide inclusion. Analysis of the rough fracture surface revealed a major concentration of iron, and trace amounts of sulfur, manganese and oxygen indicative of the base steel material.

The rough "woody" features on the fracture surfaces are ductile, as shown by the dimple rupture in Figure 10. The thick end of the fracture, which appeared to be shiny and rough in our binocular examination, are "cleavage" facets, indicating a fast fracture, probably the last portion to separate.

Further SEM examination revealed the other fracture surface to be entirely dimpled rupture, similar to that shown in Figure 10.

Optical Microscopy: The failed ring was cross sectioned away from the fracture for microstructural analysis. Figure 11 shows the inclusions in the longitudinal cross-section. The inclusion content is quite significant and is typical for a resulfurized steel.

The chemical analysis and the hardness values meet the drawing requirements.

Conclusions and Discussion: The failure was caused by use of an inappropriate material. The large inclusion, comprised of manganese sulfide (a normal inclusion found in 1144, a "resulfurized" grade of steel) was observed at the origin of cracking at the thinnest section of tapered Ring A. The circumferential stresses applied to the ring during tightening created a crack and ultimately a rapid fracture of the ring. This was a fracture that occurred during a single application of load. No evidence of fatigue or other forms of "progressive" fracture were observed.

It is not known whether over torquing caused this particular failure. However, a large inclusion in an area of high stress/thinnest cross-section is more prone to fracture than another thicker area (under lower stress) and with smaller/fewer inclusion. The most adverse effects of non-metallic inclusions occur when the stress direction is perpendicular to the length of the inclusion and to the drawing direction, such as in the tapered rings.

The material meets the drawing requirements for 1144 steel, per ASTM A311. A relatively high inclusion content is normal for this grade of steel. Specifying the contents, sizes and shapes of inclusions is not applicable for "resulfurized" grades, per

ASTM A311. Therefore, when large, randomly distributed inclusions happen to be located at the thin portion of the tapered rings, failures can occur under normal torquing loads.

Recommendations: Since the tapered rings were stressed circumferentially, (i.e. transverse to the drawing direction), selection of a material with: 1) a low inclusion content, such as a non-resulfurized grade; and 2) fabricated by hot-rolling rather than cold drawing should improve the product.

If the Power Lock was to be used **at room temperature or above,** two steels that could be procured to meet the above criteria are: 1) ASTM A321 (equivalent to AISI/SAE 1055); and 2) ASTM A322, Grade 4130 (AISI/SAE 4130). Both steels should be procured in the annealed condition for machining. Note: The machinability of these steels is lower than that of 1144. After machining, the steels should be heat treated by austenitizing, quenching, and tempering to the drawing-specified hardness.

If the Power Lock was to be used in **cold** environments (i.e. 32°F or lower), then the steel selected must possess, in addition to the above criteria, adequate impact strength at -50°F. Steels such as the "high strength low alloy" (HSLA) grades per ASTM A633, or the ship hull steel HY-80 alloy can be used. The HSLA alloy A633 can be purchased, machined, and used in the normalized condition. The HY-80 must be austenitized, quenched and tempered after machining.

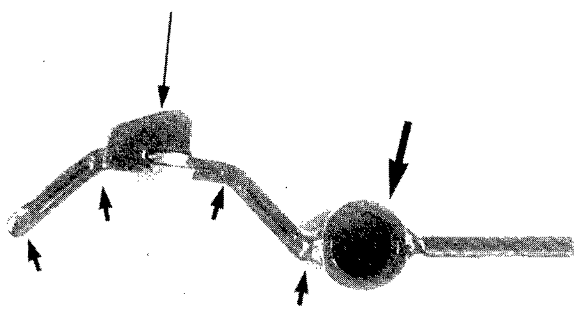

Figure 1. Overall view of a new pawl. Small arrows are pointing to the welded spots; the long thin arrow is showing the weight and the thick arrow is showing the fulcrum bushing. Mag. 0.6X

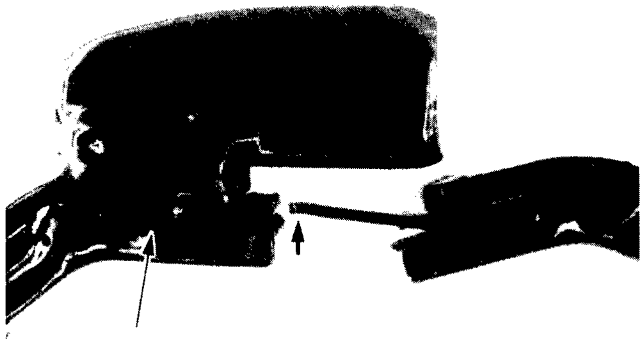

Figure 2. A fractured pawl; the smaller arrow is pointing to the plastic deformation and the longer arrow is showing the cracked weld. Mag. 2.2X

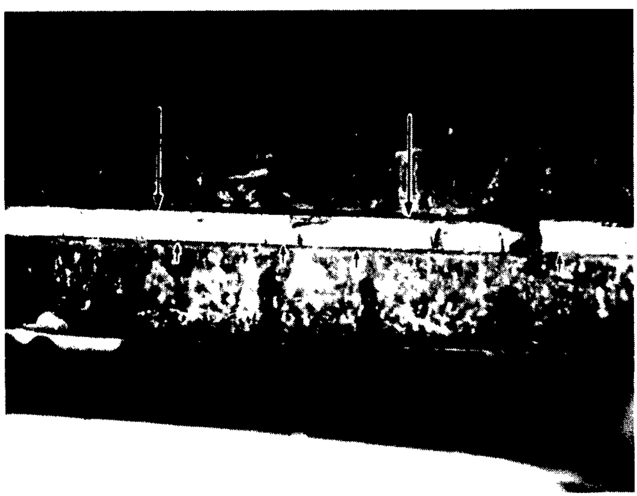

Figure 3. Overall view of the fracture surface of sample #1. Small arrows are pointing to the origins, longer arrows are showing the overload area. Mag. 6.4X

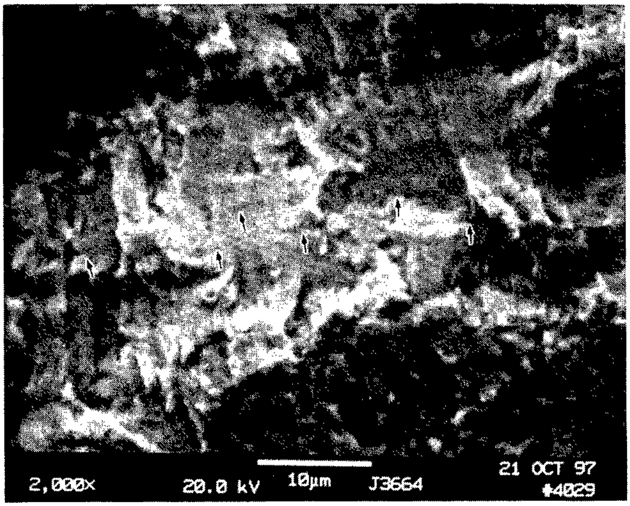

Figure 4. Higher magnification SEM photograph revealing fatigue striations (arrows) emanating from one of the origins. Mag. 2,000X

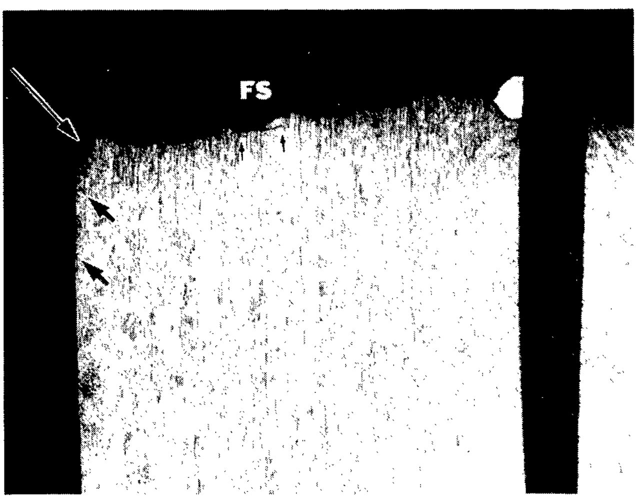

Figure 5. Mounted cross-section through one of the origins of sample #1. The longer arrow is pointing to the origin; small arrows are showing the secondary cracks on the FS. Thick small arrows on the left-hand side are showing other fatigue cracks initiating. Mag. 100X

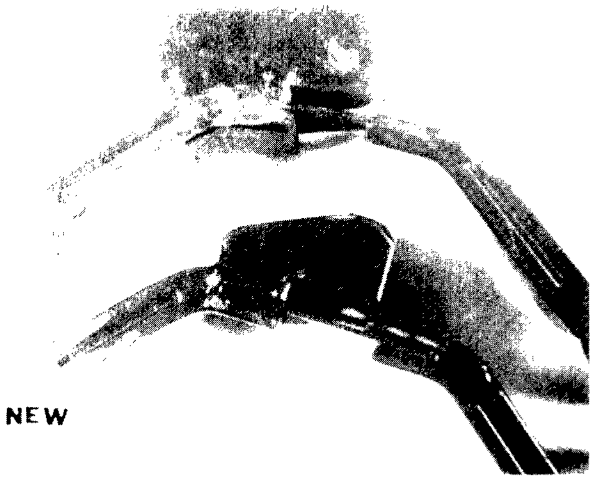

Figure 6. Suggested new pawl tip design for the existing pawls. The upper pawl is showing the tip design currently in use. Mag. 1.25X

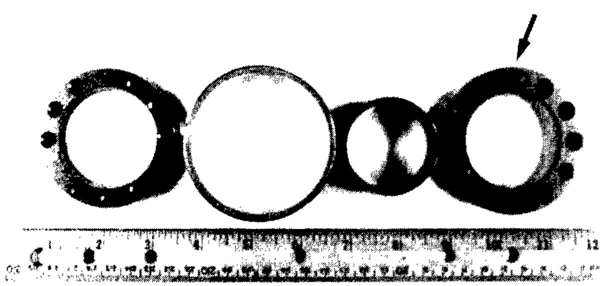

Figure 7. Overall view of the disassembled "Power Lock". The arrow is pointing to the crack in Ring A.

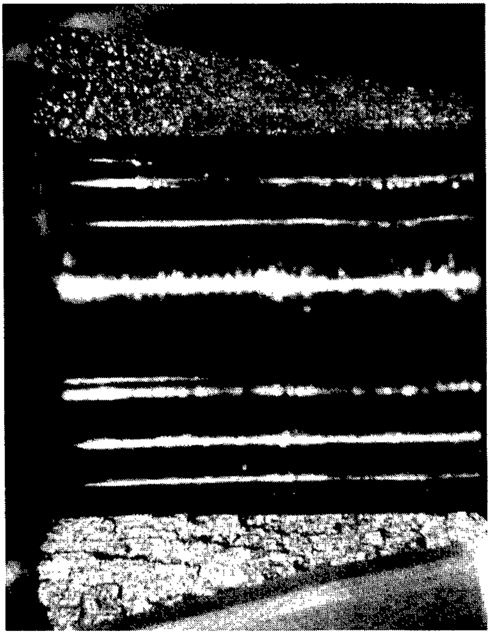

Figure 8. Broken open crack. Mag. 8X

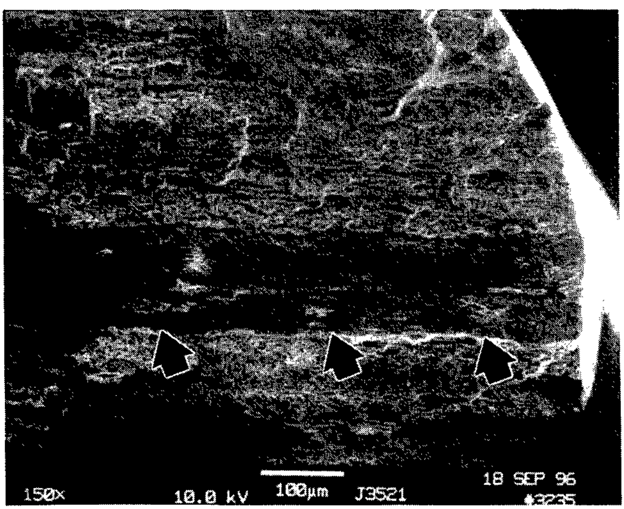

Figure 9. Higher magnification SEM fractograph reveals a long, smooth, flat area

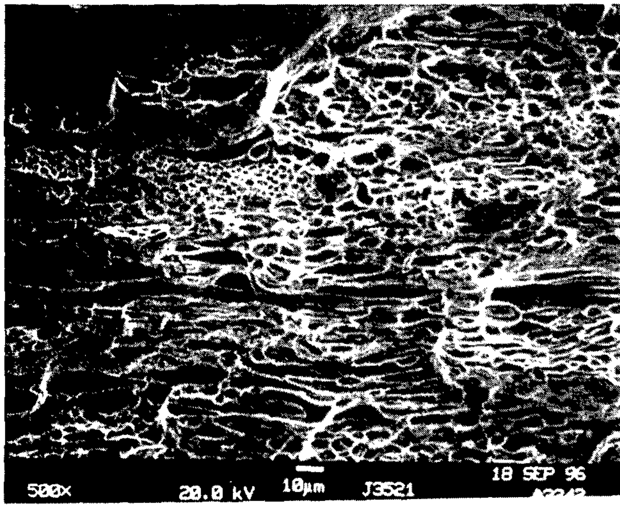

Figure 10. Ductile dimple rupture type of fracture observed in the "woody" areas of the fracture surface. Mag. 500X

Figure 11. Mounted longitudinal cross-section through ring A showing manganese sulfide inclusions. As-polished. Mag. 100X

Characterization Testing- A Predictive Maintenance Advantage

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Abstract: Knowing that a traditional time-directed preventive maintenance program is limited in its flexibility and effectiveness, the CHAR 921 characterization system software was developed as an open architecture design. This enables linking to additional data base modules and integrating predictive maintenance data collection and data analysis into a single system. Applications for which the Characterization System is most effective:

- Distributed Control Systems (DCS)
- Fire Protection/Security Systems
- Pressure Transmitters
- Power and Instrumentation Cables
- Relay Coils
- Motors
- EMI (Noise Problems)
- RTDs
- Solenoids
- UPS Inverters/Chargers
- Flow Transmitters
- Thermocouples

By taking advantage of the synergistic benefits realized when the results of several techniques are brought together, power plant management has a powerful tool which directs the focus of maintenance activities to "real time" equipment condition needs and not simply performing maintenance as a function of time.

Keywords*:* Characterization system, predictive maintenance, condition monitoring, time domain reflectometry, transmission line, circuit modeling, lumped element impedance, distributed element impedance.

Introduction: A characterization system is a combination of electronic measurement instruments and database management under computer control. The hardware provides the means to accurately measure those electrical parameters that have already been defined through standards and manufacturer's specifications: resistance, capacitance, inductance, and time domain reflectometry signature. The software provides the ability to manage the electrical test data. The software has two equally important roles: first, the acquisition of the data so that it is truly representative of the accuracy of the test equipment; and second, the storage, retrieval and processing of the data so that it can contribute to improved equipment operation. The electrical variables being characterized were always known to be important. In the past, to make life easier for the end user, a manufacturer would pick the most critical and most easily measured variable(s) for monitoring. For example,

winding resistance might be the critical parameter for a motor to be checked periodically. Additional tests to measure capacitance or inductance might only be specified for troubleshooting.

Circuit Characterization: Characterizing a circuit is based on the concept that operational circuits contain both lumped and distributed impedance elements. Basic courses in alternating current (AC) theory treat the various circuit parameters as discrete or "lumped" quantities. The passive circuit elements include resistance (R) measured in ohms, inductance (L) in henrys and capacitance (C) in farads. For the lumped elements it is assumed that they have negligible physical size and are essentially pure.

1. Resistor - neglect the wire wound inductance.

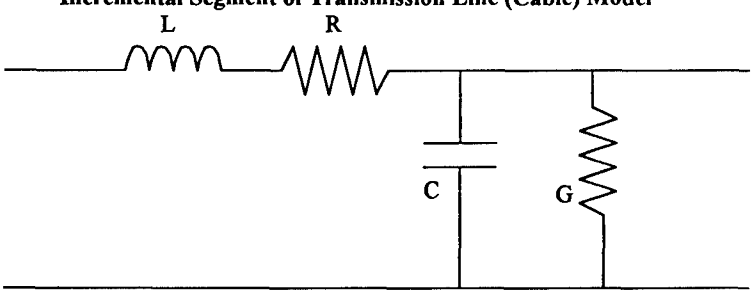
2. Inductor - neglect wire resistance and wire to wire capacitance

3. Capacitor - neglect lead wire resistance

The concept of negligible physical size simply means that distance between leads is insignificant. Distributed element impedance brings size into consideration such that you can't ignore the distance between leads or the time required for current to travel through a relay coil or motor winding. A cable is the best example of distributed element impedance. The Characterization System uses conventional test equipment for measurements of the lumped element impedance and Time Domain Reflectometry for measuring the distributed element impedance of a circuit.

Characterization Data : Analysis of characterization data is based on the understanding that nearly all power and control circuits can be treated as two port networks and analyzed as radio-frequency (RF) transmission lines with a load at the end of the line. This allows circuit components to be separated in time and analyzed individually even while testing from a remote location.

Incremental Segment of Transmission Line (Cable) Model



L = Inductance
R = Resistance
C = Shunt Capacitance
G = Shunt Conductance

In the model above, R is the series resistance of the line, it includes both conductors. It varies with frequency because of skin effect. It may be negligible or quite large, typically it is between these extremes. Note that the dimensions of R must be ohms/unit length, that is ohms/meter, ohms/feet.

The series inductance, L, occurs because the magnetic flux surrounding each incremental length of line links with the adjacent incremental lengths of conductor on either side. The effects of the series L may also be large or small, depending on line frequency, and application. The units of series inductance are henrys/unit length.

The shunt conductance, G, causes leakage currents which dissipate power. It is caused by less-than-infinite insulation resistance. For a well-insulated overhead electric power transmission line, G is nearly zero. This is not true for most other transmission lines, however. The units for shunt conductance are reciprocal resistance per unit length, that is mhos/unit length or siemens /unit length.

The shunt capacitance, C, is due to the physical proximity of two or more conductors separated by a dielectric. It causes displacement currents which dissipate no power but may be troublesome for other reasons. These may be negligible for a short, overhead, power line, and immense for a buried high-voltage cable. The units for shunt capacitance are farads/unit length.

We will examine each of these parameters and note the contribution that changes in each makes to the probability of circuit failure.

Wire series resistance (R) is determined prior to manufacture of the wire by choice of conductor size, physical configuration (for example, stranded or solid) and material. The choice of each is made with regard to allowable current density, amperes/unit area of conductor, for an acceptable heat rise in the expected operating environment. The required mechanical properties (tensile strength and flexibility, for example) are also factors in conductor design. The only change in series resistance that we may expect under normal operating conditions, after the conductor is placed in service, is the change due to variations in temperature. The resistance change with temperature is a well-understood phenomena, and is given by: $Rt_2 = Rt_1 [1 + \propto (t_2 - t_1)]$

Rt_2 = Resistance at temperature t_2, ohms
Rt_1 = Resistance at temperature t_1, ohms
t_1 = Present temperature, degrees Celsius
t_2 = Reference temperature, degrees Celsius
$\propto$ = Temperature coefficient of resistance
= 0.0039 for copper, 0.001146 for aluminum, per degree Celsius.

Using the above, we may investigate changes with temperature. A circuit consisting of 1000 feet of solid copper 12-gauge wire has a resistance of 1.652 ohm at a temperature of 59^0F (15^0C), for example. At 131^0F (55^0C) its' temperature increases to only 1.91 ohms,

an increase of 15.6%. Changes of this magnitude are easily managed, their effects are minimized by careful system design. Major resistance changes from other causes are most unlikely. Remember that resistance is: $R = \frac{\rho l}{A}$ ohms

ρ = Resistivity, ohm-meters
l = conductor length, meters
A = Conductor cross-section area, meters

The resistivity is a property of the conductor material, it is fixed at manufacture, and thereafter can vary only with temperature. A non temperature-related gross change in resistance then requires a gross change in either conductor length or cross-sectional area, or both. Such could conceivably be caused by severe mechanical damage, or severe corrosion which reduces the conductor cross-sectional area by a significant amount over a considerable length. Termination or splice problems are a far more likely source of series resistance changes, however. Each requires a breach in the protective insulation which is a possible entry point for moisture or other contamination. Two other possibilities must also be noted.

1. A less-than-perfect connection can lead to heating, loosening, and eventual arcing and failure.

2. If vibration is present, care must be taken at installation to properly distribute the bending of the conductor. Failure to do so will lead to metal crystallization and eventual failure.

We may summarize all of the above in a few words. Resistance changes in the line are highly unlikely in the absence of gross mechanical or chemical damage. Resistance changes in splices or terminations are quite possible, however.

Line series inductance (L) is due to the flux surrounding an incremental length of line linking with the immediately adjacent lengths on either side.The amount of flux for a given current is strongly affected by the permeability of the medium surrounding the conductor. Remember that the permeability of iron and iron alloys is high, about 2000 times the permeability of air. Air and most other materials have a very low permeability, they are magnetically transparent. We may immediately recognize that series inductance will be affected if we insert a twisted-pair line in a steel pipe, for example. The effect may be less than we expect, however, for the flux is largely confined to the space between the conductors. Once installed, changes in series inductance are highly unlikely. It is difficult to envision a situation in which a ferromagnetic material is placed in, or removed from, the space between the conductors, so we may remove such changes from our subjects for consideration.

Line shunt capacitance (C) in a uniform, undamaged, uncontaminated line is a function of conductor size and spacing, and of the dielectric properties of the material surrounding the conductors. The conductor insulation is usually the only material of interest. The manu-

facturer selects an insulation with due regard to many factors. Its' mechanical properties include physical strength, flexibility, and ease of application at manufacture. Voltage withstand capability is important, as is expected service life. The insulation will be assaulted by heat, radiation, chemicals, and voltage stress. It must withstand all expected hazards without significant loss of mechanical or electrical capabilities. For most applications, the dielectric constant, or relative permittivity, is low, or absent from, the list of factors in choosing an insulation. Changes in this will be of major interest in the use of Characterization test data. Changes in dielectric constant causes changes in line capacitance. They are usually clear indicators of present or incipient circuit problems. They are highly likely and are easily detected and localized with Characterization system testing. Basic physics describes the parallel-plate capacitor whose capacitance is given by:

$C = \underline{\varepsilon A}$ Farads

ε = permittivity of material between plates, Farads/meter

A = area of each plate, meters

1 = distance between plates, meters

The permittivity is usually given as:

$\varepsilon = \varepsilon o \varepsilon r$

εo = permittivity of a vacuum

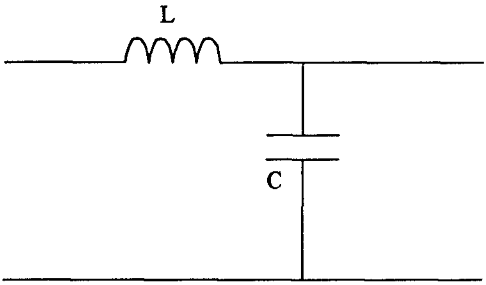
εr = relative permittivity of dielectric used

$= \dfrac{10^{-9}}{36} \dfrac{\text{Farads}}{\text{meter}}$

Relative permittivity varies widely. A vacuum has a relative permittivity of 1.0000 by definition. Values for some other common materials are shown below.

Distilled Water	Relative Permittivity
Air	1.0006
Polystyrene	2.7
Rubber	3.0
Bakelite	5.0
Flint Glass	10.0
Distilled Water	81.0

Simplifying the cable model shown earlier, to a lossless line model allows us to easily define changes in the characterization data of individual circuits by simply evaluating the lumped element impedance for change and then correlating the change to a location in the circuit by evaluating the distributed element impedance which is a function of time (as seen by the TDR). Since most transmission lines are nearly losses, we will only consider the reactive components L & C in a simplified model of our incremental line below:



L = Inductance
C = Capacitance

If we could immerse this two-wire line in water, we would see the shunt capacitance measurement increase by a factor of ≈ 80. Since the characteristic impedance for the lossless line is: $Z_c = \sqrt{Z/C}$ ohms; a change of 80 in the value of C leads to:

$Z_c = \sqrt{Z/80C} = \sqrt{1/80} \times \sqrt{L/C} = 0.111 \times \sqrt{L/C}$ ohms. So if the characteristic impedance of our model was 200 ohms, it now reduces 22.2 ohms as a function of moisture intrusion of the dielectric. This is not an uncommon occurrence in a power plant or industrial facility. For most instrumentation and control circuits, this change in characteristic impedance, is in itself of little consequence; the circuit will usually operate normally. The intrusion of moisture into the conductor insulation isn't necessarily harmful in itself, however the long-term prognosis is usually failure.

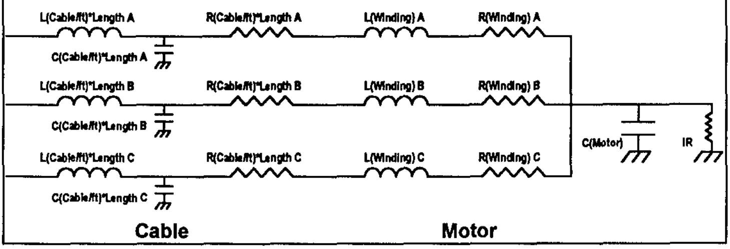
Understanding the electrical parameters being characterized and factors which can affect these test parameters allows comparative analysis to be automatically performed by the characterization system. Analysis reports are generated automatically using predefined tolerances for the various circuits being tested. Afterall, the idea of predictive maintenance is to establish a program for the equipment of concern which allows comparative analysis of test data in advance of actual failure. Of course, the goal is to do this in the same amount of time, or less, than was originally allocated to perform any testing being done as part of an existing Maintenance Program.

Case Study: The following case study describes characterization testing of motors for predictive maintenance. This summary will focus on comparison of the most critical electrical parameters being trended and provides insight on how the determination of electrical condition of each motor are prioritized for maintenance.

Background: The analysis of the motors begins by modeling each of them as shown in Figure 1. The model consists of the resistance, capacitance, and the inductance of both the cables and the motor. Stresses that cause electrical failure include differential thermal stresses, different coefficients of expansion, varnish weakening at high temperatures, magnetic force due to winding currents, environmental contaminants and moisture. These

stresses cause looseness, motion, and wear of the insulation. Each of the materials used to fabricate motor insulation systems has different sensitivities to these stresses. A Characterization System test on a motor, made from the motor control center or switchgear, will determine the quality of the cable and motor insulation, condition of the motor connections, and will provide impedance data which can be flagged at predetermined values for changes in capacitance, inductance, dissipation factor etc. Determination can be made regarding problems with the motor or cable without having to disconnect the motor from the cable. When trended this data can provide a meaningful and accurate assessment of the stator winding insulation system.

Figure 1: Reactor Coolant Pump Motor Analysis Model



The critical test measurements automatically acquired, analyzed and trended with the Characterization System are described below:

1. loop resistance

2. loop impedance

3. insulation resistance / polarization ratio

4. capacitance/dissipation factor

5. time domain reflectometer signature

Details of two critical factors used in analyzing motors are: <u>Dissipation Factor</u>: The dissipation factor is a **key electrical indicator** for predicting failures with motors. Purely conductive losses between conductors are small in a well insulated line. There is however, also a "dielectric hysteresis" loss which must be included in the shunt conductance . It will be recalled that the line capacitance stores energy of : $1/2\ CV^2$ joules-second. When energized by the AC line, capacitance stores energy for 1/4 cycle, returns it to the system during the next 1/4 cycle etc. Ideally all stored energy would be returned, but this is not the practical case, a small amount is dissipated as heat in the dielectric. If we assume that energy is stored by stressing or moving dielectric atoms or molecules then we must assume there is friction, for energy is lost when heat is developed. The dissipation factor then is a function of shunt conductance where $G = 2\pi f \times PF$ mhos, where PF is the

dielectric dissipation factor. It equals the power factor for the high-quality dielectric commonly used, and is small for most large motors .

Capacitance: Another key indicator for insulation condition is capacitance. In increase in capacitance can sometimes indicate moisture intrusion, while thermally aged windings will show a decrease in capacitance over time, since the air-filled voids/delaminations have a lower dielectric constant, and therefore capacitance. Windings containing moisture will have a higher capacitance since the dielectric constant for water is $\approx$80, compared to 4 for epoxy-mica.

Conclusion: Based on the Characterization data a decision was made to also replace the stator for a second motor. Upon removal and disassembly at the OEM facility, the extent of stator system degradation was obvious and correlated to the characterization data analysis. The characterization data accurately assessed the condition of the motor and most likely prevented a motor from failing after the plant was back on-line. Characterization testing for predictive maintenance and troubleshooting can enhance effective/efficient resource allocation when used as part of a comprehensive condition monitoring program for all electrical equipment.

Analysis of vital subsystems of technical system maintenace

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Abstract: The fundamentals of logistic support for the technical system maintenance contained in and described by the basic maintance subsystems, have been presented in this paper. The structure of the maintance system for major business was described throught the folloving subsystems: subsystem for the management of material and spare part supply process; subsystem for operation management; subsystem for technical diagnostics; subsystem for complaint processing; subsystem for reporting and data processing and subsystem for personnel planning.

This allows a multidisciplinary tretment of the technical systems throught their life cycle (begining with the preliminary research into the needs for supply or projecting, throught the process of production and installment, exploitation, to final wearing out) in order to manage the technical state and reliability of the technical subsystems, accompanied by clear decision documentation.

Key words: CIM; expert system; logistic; quality tools.

Introduction: The notion of maintenance comprises a series of procedures needed for preventing the incidence of the "failing" states, i.e. restoring the system from the "failing" state to the "operating" state, in the given time and environmental conditions. The process of technical system maintenance is characterized as an accidental process, since accidental changes of a number of magnitudes are inherent, inseparable from the process of maintenance. The final purpose of the maintenance process is to create bases reliable enough to, eventually, bring us to an improvement of all functions of maintenance, i.e., to an increase of technical system effect; a decrease of failures, by improving the level of technical system reliability; defining the bases for constructive-technological innovation, reconstruction (modification) of the system, work productivity increase in maintenance; a decrease in spare part stock, as well as an increase of the efficacy of enterprise management.

The development of industrial society and, more recently, information society, the consciousness of the importance and role of technical system maintenance has also developed although, for a long time, it had been regarded as isolated so that the models, i.e. maintenance concepts, did not keep pace with technical system development. Maintenance has evolved to the maintenance according to the state, terotechnology, integral logistic maintenance support, as well as maintenance in CIM (Computer Integrated Manufacturing) environment.

Maintenance should represent a multidisciplinary treatment of technical systems, throughout their life cycle, involving all procedures, methods and techniques which should be applied in order to keep a technical system, as long as possible, in proper (operating) state, so that during its expected lifetime it operates with the needed reliability, productivity and economy.

Fig. 1 represents the activities and mutual relationships during the exploitation cycle of the product. The block scheme, in fig. 2, shows the stages of technical system maintenance [1]. In the first stage, a technical description of the system is done, as well as its decomposition into subsystems and units. During the second stage, characteristic units to be maintained are sorted out by applying the Ishikawa method (Cause - Consequence Diagram) and Pareto (ABC) analysis, in order to detect the most influential units and to estimate the largest expenses. In the third stage, the methods of maintenance are determined, using the FMEA (Failure Mode and Effect Analysis) method of risk estimation. Following the choice and implementation of the specific maintenance method, in the fourth stage, the condition of equipment is analyzed.

Modern strategy of maintenance involves the techniques and procedures which provide documented decision-making, concerning the condition of equipment, tasks and measures to be undertaken, comprising a high level of scientific and multidisciplinary knowledge. The strategy can be technical and managing. Technical strategy is represented in fig. 2. Managing strategy gives an explanation of how to integrate the human factor, politics, equipment and reality in order to fulfill the contemporary business demands. Maintenance system is comprised of specific conceptual, organizational and technological solutions for managing the process of maintenance. The concept of maintenance process represents its most important features, since it considerably influences general quality of maintenance, depending on the principle on which decision-making about the procedure of maintenance is based. Concerning the concept, there are two basic solutions: preventive and corrective maintenance. These concepts can be linked into combined maintenance. In preventive maintenance, the needed procedures are performed before the appearance of failure, while in the corrective one, they are done after the appearance of failure.

Preventive maintenance according to the condition represents a modern conception of technological system maintenance, and a new approach to maintenance, based on performing proposed diagnostic examination (condition control), while the results, symptoms determine the application of appropriate maintenance procedures. Within the method of preventive maintenance, we do not distinguish only two extreme conditions,

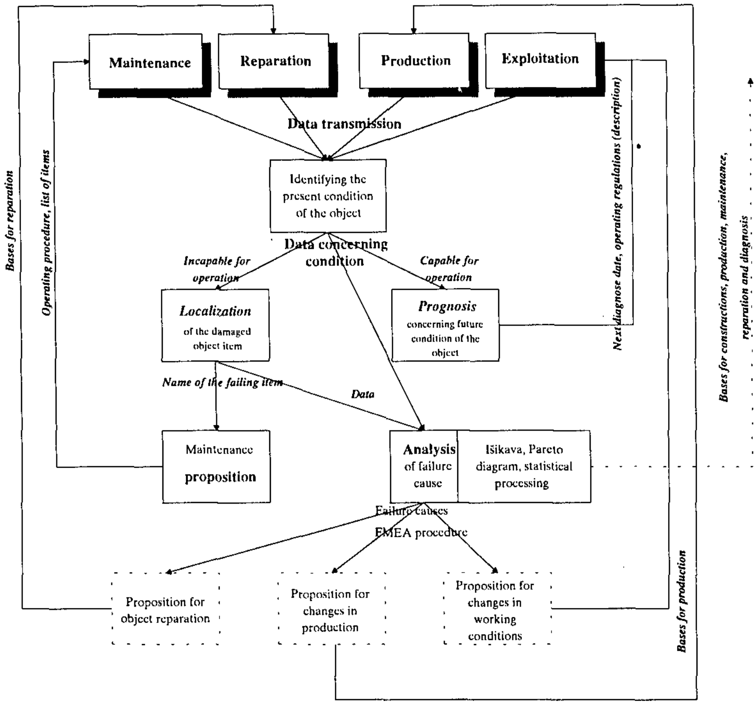

Figure 1. Activities during the use

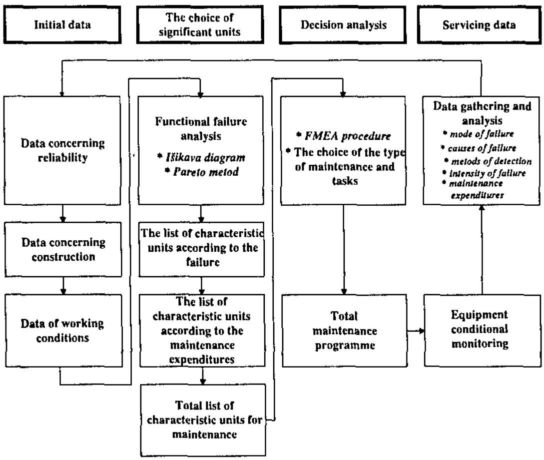

Figure 2. Basic stages and procedures of product maintenance

the state of failure and the state of operation, but also a large number of states between these two extremes. Thus, sudden failures, which are mostly caused by accumulated defects are minimized.

Instead of numerous experimental-pragmatic and/or scientific analytical conclusions about the system of maintenance, one conclusion is self-imposed:: maintenance comprises a factory (in factories).

The theory and practice of maintenance is greatly influenced by the tools, methods and techniques originating from the Japanese philosophy of production, which play a special role in increasing the level of productive systems (Toyota system - a productive-business system without making stocks; IT - Just in Time principle; Zero QC - Zero Quality Control or "Zero Defects"; TQC - Total Quality Control, etc.).

As shown in figures 1 and 2, the techniques of quality engineering comprise the essential engineering tools for a modern system of maintenance. These methods and techniques can be classified according to the area of usage in an enterprise (for product development, for an evaluation of quality provision, production management, etc.), or according to the steps they support in problem-solving (data gathering, problem identification, problem analysis, analysis of the relation between the cause and result, corrective activities, and result-effect verification). The mentioned tools can also be represented as Q7 - Seven Quality Tools (Q1 - Failure Summary List; Q2 - Histogram; Q3 - Control Charts; Q4 - Pareto Diagram; Q5 - Correlation Diagram; Q6 - Brainstorming; Q7 - Ishikawa Diagram); M7 - Seven Management Tools (M1 - Affinity Diagram; M2 - Relation Diagram; M3 - Tree Diagram; M4 - Matrix Diagram; M5 - Portfolio; M6 - Network Plan; M7 - Decision-making Plan); Information Quality Tools [2] (Internal Audit; Benchmarking; EDM /Engineering Data Management/; Statistical Methods; QFD /Quality Function Deployment/; FMEA).

Representation of vital maintenance subsystems. Having entered the sixth manufacturing ?poque, in 1985, referred to as an acronym, CIM - Computer Integrated Manufacturing, the conditions were created to develop a contemporary theory and practice of maintenance, maintenance in CIM environment. The CIM concept of enterprise management is, currently, the leading concept defining the organizational structure of an enterprise, directed towards the market. This concept also involves the JIT (Just in Time) concept, relying on the philosophy of the least possible capital stock keeping, i.e., the philosophy of manufacturing without any stocks.

By decomposing the basic modules of the CIM concept into lower levels, the role of maintenance can be shown within this concept, within the frame of production planning (PPS - Production Planning System) and management [3].

The basic objectives of maintenance planning are strictly dependent and, in great measure, identical with the basic objectives of production itself, and are usually solved as an integral part of the information system of an enterprise.

The basic functions of maintenance planning are: maintenance programme and planning; technological procedures of maintenance; time normative; material and spare part normative; planning for means of work on the maintenance jobs; operative and technical documentation processing; substitution plans for import of parts, materials, technology; planning for detection and removal of weak points; planning for modernization and reconstruction.

The structure of maintenance system for major business systems can be described through the following subsystems:

- subsystem for the management of material and spare part supply process
- subsystem for operation management
- subsystem for technical diagnostics
- subsystem for complaint processing
- subsystem for reporting and data processing and
- subsystem for personnel planning.

Subsystem for the management of material and spare part supply process. The process of material and spare part supply involves: needs analysis, supply or production (self-production or co-operant production), storage etc.. Spare parts necessary for technical system maintenance, i.e. the process of production, comprise an important element of logistic support of maintenance, and have a special role in the quality system of the management of maintenance process.

Part consumption for various technical systems and time intervals can be efficiently determined by Pareto (ABC) analysis of the significant minority and insignificant majority. By means of Pareto analysis application, it is determined that 10% of the parts comprise 70% of the total need for spare parts in railway vehicle reparation. This conclusion is very important because it indicates which spare parts should be held on stock.

The role of spare parts covered by supply in maintenance is significant, much greater than the role of spare parts self-produced in the workshops. This means that the quality of maintenance is also considerably influenced by external factors, introduced by the process of supply. That is why it is necessary to consider a number of target magnitudes and their effects (not only the prices). The supply process is characterized by the complexity increase of the parts to be supplied, where it is more and more usual to order the whole production systems, i.e. pre-constructed substructures, and less and less common to make orders of individual parts. This complexity, of course, increases the importance of deliverer's development of the product, and thus, his expenses, as well as the risk of development are also increased. The limited scope of the user's part production, as well as the increased demands for reliability and quality of the delivered products, make the necessity of the deliverer's involvement into the user's manufacturing trends even more pronounced. This can be made possible by minimizing the number of deliverers (as a rule, 1-3) per one part supplied, as well as by defining the deliveries by means of long-term, detailed contracts.

The common, contemporary practice of quality provision in supply, which is concentrated on examining the goods posterior to delivery, is not the expected future concept. The concept of quality provision includes all areas of quality provision, concerning the parts to be supplied.

The significant elements of the quality system also refer to handling, storage, packaging, conserving, as well as to delivery of materials and parts.

Subsystem for operation management. One of the most important functions of maintenance planning is also the management of activities, events, and procedures necessary for, or greatly influencing the maintenance process, including an application of specific methods and means.

The analysis of this element of logistic support should encompass the use of network plan for defining the "critical route" of the process, relation diagram for finding the needed relations, tree diagram for easier understanding of position of a part within a system, as well as QFD (Quality Function Deployment) quality house on the second, third and fourth levels. QFD Method usage allows decomposition of a product into certain systems, by making use of the second quality house, specification of production technology through the third quality house, while parameter definition is performed by making use of the fourth one. This new method is also efficiently applied in the maintenance domain.

This area is also concerned with the problem of refuse and additional production. Refuse and additional production make a special category of quality expenditure, internal loss expenditures. The theory and practice have shown that this category is the most important one among the quality expenses, and is often treated as a normal phenomenon in production. Enterprises are usually not aware of the real cost and causes of refuse. 10% of refuse means production more expensive for about 15%, since refuse means additional production. Increased percent of refuse or additional production can serve as a barometer of the state of overall production. It is very important to know that a systematic approach to this problem, can organize production without any refuse. The number of refuse created, additional production and satisfactory products in an operation can indicate the expenditures, and by monitoring the failures causing refuse or additional production, the real cause can easily be determined and prevented.

One of the basic initial functions of maintenance planning is also technological procedure designing, which involves technological procedure defining (primarily, the sequence), creating time normative, material and spare part normative, the choice of means of work and control (machines, tools, devices, auxiliary materials), etc. These activities are primarily based on experience and intuition of experts, and are, to great extent, supported by CAPP (Computer-Aided Process Planning) systems for automatization of technological procedure design. The current approach to the CAPP system development is based on non-algorithm programming and more frequent application of artificial intelligence method.

Subsystem for technical diagnostics. Contemporary maintenance is, primarily, a diagnostic process (condition checking), based on measurements, essential technical law application and specific empirical knowledge, so that an estimation of each system component condition can be done. Depending on the estimated condition, appropriate maintenance procedures (tuning, reparation, replacement, etc.) of aggregates and/or systems are performed. These activities are predominantly based on experience and intuition of the technologists, as well as their empirical knowledge and available information.

The crucial demands of diagnostic testing in exploitation are considerably different from the demands of production testing. Within a production process, the level of quality is defined by construction data, during the operation of exploitation the level of quality can vary, depending on the purpose of testing, different user's demands, different working environment, economy of maintenance, etc..

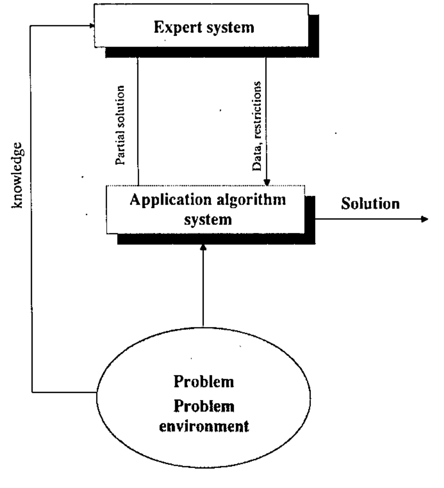

Figure 3. A software maintenance support model

The diagnostics involves: diagnostic testing for an estimation of the condition or failure on the module level; diagnostic testing for determining the cause of failures within a module; repaired module testing; complete testing in gross or general reparation.

The most effective procedure of condition diagnosing is based on an application of artificial intelligence, and primarily, on expert system application. Computers containing artificial intelligence allow a very flexible use of data, stored in them. If these data contain expert knowledge in some field, than the use of computers nearly equals consulting an expert. In this way, companies are provided with permanent possession of expert knowledge, instead of losing it when experts leave companies.

Subsystem for complaint processing. Complaints are often a current problem in production practice, but unfortunately, this problem is not approached in a systematic way, although it is well known that production can be organized in such a way, as to have an insignificantly small number of complaints, or no complaints (zero defect), where such an organization would cost less than the loss created by complaints. Complaints create an irreversible loss of time, material and energy, as well as new expenditures: classifications, analyses, additional production, refuse destruction, new product manufacturing, etc.. In such a way, companies lose even more than that: a reputation of successful enterprise, and finally, even worse, the customer.

Subsystem for reporting and data processing. Subsystem for reporting and data processing represents an integration of database and base of knowledge, thus providing on-line information about all relevant data concerning maintenance (fig. 3).

Data processing can be performed with respect to different objectives: short-term (close to the process) and long-term (beyond the operative plain, following the objectives which improve the process, e.g. weak point detection.

Data processing is a significant base for creating business regulation circuits, both internally within the plain, and on superimposed plains. Nowadays, it operates with powerful "tools", which allow adequate and accurate involvement of all business functions.

The primary objective of data processing is to contribute to quality proof demands. Data processing significantly contributes by preparing information about the product and the process of its creation, in order to provide and improve the quality of both the process and the product.

This subsystem comprises documentation management, which is an essential, unavoidable activity in every enterprise. Documentation management presupposes gross involvement of a large number of people, since the number of documents is gross, it is necessary to know where some document is kept, where it can be reached, etc..
Within the classical approach to documentation management of an enterprise, only a limited number of people is able to handle it, while it is not available to the majority of the employed.

Subsystem for personnel planning. Survival and development of an enterprise is based on a number of policies. The most important of them are: the personnel policy, developmental policy, business policy, quality policy, etc.. Personnel policy is determined, limited and, to some extent, directed by the objectives of an enterprise (developmental and business policy). By personnel policy the objectives to be achieved in some period of time are defined, as well as tasks, principles, and criteria in the domain of personnel function, together with the methods, procedures and means for achieving a goal in the domain of personnel function.

Personnel policy involves the following basic domains of activities or actions: personnel needs analysis, personnel provision (supply); distribution and promotion of personnel; personnel training; motivation and personnel safety.

The function of human resource management is basically limited to a tendency to give this resource a position similar to other business resources in the process of business management. As in the case of other production resources, it is not difficult to determine the productivity (compared to the appropriate objectives) and check the output quality, but it is more difficult, in this case, to introduce corrective measures.

A presentation of an information-expert system for the maintenance of railway tractive vehicles, created for the factory "Lokomotiva". The area of production of this factory is reparation and production of railway tractive vehicles (electric, diesel-electric, diesel-hydraulic locomotives and dollies), as well as production of railway tractive vehicles for special use.

Figure 4 shows the organizational scheme of an enterprise based on the CIM philosophy platform and global software business support. The organizational structure has 6 different modules of the CIM system: MIS - Management Information System; PPS - Production Planning System; CAD - Computer-Aided Design; CAP - Computer -Aided Planning; CAM - Computer-Aided Manufacturing and CAQ - Computer-Aided Quality. Module CIO - Computer Integrated Office, is also added the modules listed above, which integrates all office activities within an enterprise. The described organizational scheme is characterized by flat organization, without any hierarchy, thus providing direct information transmission to individual modules, as well as among the enterprise modules. CAM module should contain all examinations linked to production. This means that the tendency should be to greater self-control among the workers, abandoning the model of control performed by controllers.

The jobs on detecting defects - diagnostics, as well as the jobs concerning the technology of locomotive plant reparation have been supported by an expert system, which operates in integration with algorithm application systems. Such a configuration should allow an estimation of the solutions obtained by the algorithm systems, or their support by an expert system.

Conclusions. The following are the conclusions on the above said:

The proposed concept of maintenance is based on the CIM enterprise concept.

It is pointed out that information and people represent the crucial elements of possession of an enterprise. The more an enterprise accepts this essential concept, further cherishing and developing it, the more successful it will be.

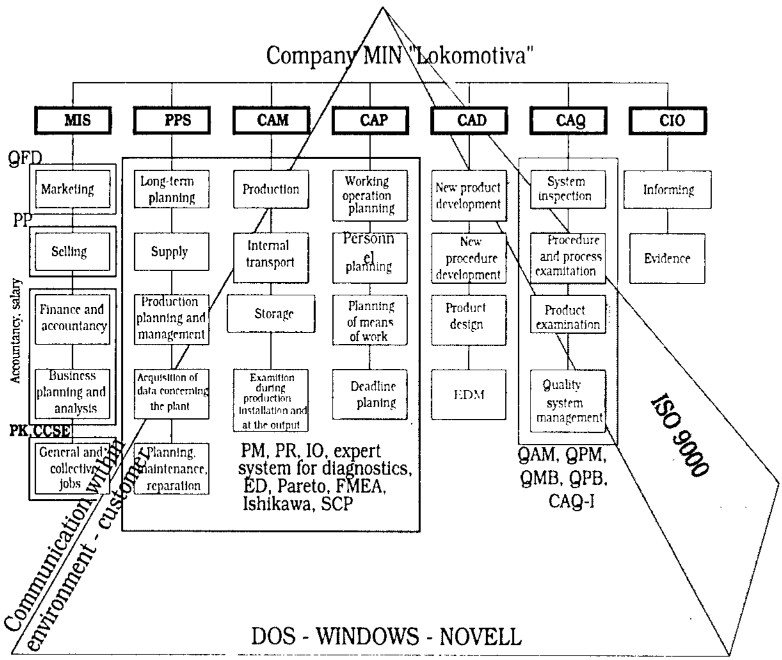

Figure 4 A model of organizational structure and software support to the reparation of railway tractive vehicles in the factory "Lokomotiva"

The basic process of contemporary maintenance is a diagnostic procedure (condition control), based primarily on measurements, although sorting out what should be measured, as well as result interpreting are also of importance. This paper suggests a solution to the problem, by an application of artificial intelligence, i.e., expert systems.

Computers enriched by artificial intelligence allow a very flexible use of data, stored in their memory. If these data contain expert knowledge from some area, then the use of computers nearly equals consulting an expert.

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